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Formation of the Viking Moraine, east-central Alberta: geomorphic and sedimentary evidence.

by

Darren Boyd Sjogren ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Department of Earth and Atmospheric Sciences

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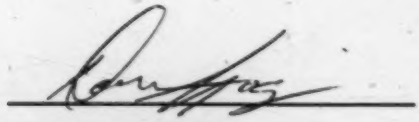

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The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled *Formation of the Viking Moraine, east-central Alberta: geomorphic and sedimentary evidence* submitted by Darren Boyd Sjogren in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

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This thesis is dedicated to

Annie Frisk, my grandmother

and

Eva Sjogren, my mother

in appreciation for their unwavering support and encouragement.

ABSTRACT

Inferring the genesis of glaciogenic landforms is often difficult. The combination of limited or lacking sedimentologic data and the likelihood of process continua makes many interpretations tenuous. It is therefore necessary to investigate not only the sediments contained in the landforms but also their topographic setting, geomorphic characteristics, and association with other landscape elements. This thesis incorporates the analysis of geomorphic and sedimentary characteristics at several scales to infer the formation of part of the Viking Moraine in east-central Alberta. Visualization of landform shapes and associations is greatly aided by the incorporation of shaded relief maps derived from digital elevation models (DEMs).

On a regional scale, landforms are arranged into packages which suggest that widespread erosion was instrumental in isolating the different landform suites. This erosion is interpreted to have been performed by catastrophic discharges of subglacial water. At least one subglacial flood initially occurred as a sheetflow but it was progressively channelized due to the instability of the flow and the spatially variable erosion of the basal ice and subglacial material. Investigation of individual landforms within the Viking Moraine substantiates this interpretation in terms of their topographic, geomorphic, and sedimentologic characteristics. Erosional channels have convex-up long profiles and contain hummocky terrain composed of bedrock and glaciogenic material. The presence of glaciogenic material in some channels indicates that the channels preexisted the erosion. Hummocky terrain is composed of stacked subglacial sediment, horizontally banded diamicton, and/or bedrock. The complement of different sediment types indicates a complex history of entrainment and deposition that reflects temporally dependent polythermal basal conditions. The combination of complex thermal conditions at the base of the ice and erosion by subglacial water best explains the emplacement and subsequent erosion of the subglacial materials found in this part of the Viking Moraine.

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CHAPTER ONE: PROBLEM STATEMENT AND STUDY AREA.

Problem Statement

There is a need to reevaluate regional reconstructions of the timing and style of glaciation on the Canadian prairies. Most past studies in Alberta have focussed on mapping glacial deposits for three reasons: first, to establish the number of Laurentide and Cordilleran glaciations in the area; second, to determine the extent and timing of continental glaciation(s), and; third, to determine whether an ice-free corridor existed between the Cordilleran and Laurentide ice sheets throughout Late Wisconsin time, enabling the peopling of North America. Largely for these reasons glacial studies have been predominantly regionally oriented and concerned with chronology. Glacial studies have been conducted on the premise that the genesis of glacial landforms is known and that landform associations can be used to infer paleoenvironments and glacial dynamics. Given the recent explosion of knowledge in glacial geomorphology, glacial geology, glaciohydrology and ice-sheet modelling it is necessary to reevaluate the genetic assumptions upon which these regional reconstructions are based. Critical reevaluation of traditional theories on landform genesis inaugurates a new era in glacial studies in western Canada where the glaciohydrology and glacial dynamics are not implicit.

Many glacial landforms such as drumlins, flutings/remnant ridges, and hummocky terrain, have traditionally been linked to formation by the direct action of glacial ice (either by active or stagnating ice). A new hypothesis, originally proposed by Shaw (1983) to explain the formation of drumlins in northern Saskatchewan, invokes erosion and/or deposition by large subglacial sheetfloods to account for many glacial landforms. This hypothesis suggests that large volumes of water drained catastrophically beneath the Laurentide ice sheet, eroding the basal ice and subglacial sediment. In doing so, these floods produced erosional and depositional landforms including; drumlins (Shaw 1983; Shaw and Kvill 1984; Shaw and Sharpe 1987; Shaw et al. 1989; Shoemaker 1995), flutings/remnant ridges (Shaw 1996), hummocky terrain (Rains et al. 1993; Munro et al. 1996), Rogen moraine (Fisher and Shaw 1992), and large tracts of scoured bedrock with superimposed s-forms (Shaw 1988; Colhoun and Adamson 1989; Sharpe and Shaw 1989; Kor et al. 1991; Shaw 1994, 1996). Progresssive channelization of inherently unstable sheetfloods (Walder 1982) resulted in mega channels, tunnel channels (Brennand and Shaw 1994) and channeled scabland (Sjogren and Rains 1995). Spatial variations in flow competence, depth, and flow routing

explain variations in the amount of material eroded and location of sediments deposited. Estimates of instantaneous flood discharges are in the order of 10^7 m^3/s and total flood volumes are estimated at 8.4×10^4 km^3 (Shaw et al. 1989, 1996). Shoemaker (1995) questioned these large volumes, suggesting that less meltwater is required if effects of corrasion by suspended sediment, in addition to melting, are taken into account. Nevertheless, the impact of these meltwater inflows on late glacial climate and ocean responses would have been significant (Shaw 1989). Blanchon and Shaw (1995) have linked the episodic drowning of reefs in the Caribbean-Atlantic region to large sub- and proglacial meltwater influxes. Smith and Fisher (1993) and Fisher and Smith (1994) hypothesised that the open-channel paleoflood from glacial Lake Agassiz to the Arctic Ocean was responsible for reorganization of global circulation patterns and termination of the Younger Dryas. Catastrophic inputs of glacial meltwater, such as those envisioned by Shaw et al. (1989) and Smith and Fisher (1993), would have had significant effects on extraglacial geomorphology as well as atmospheric and ocean circulation.

The Livingstone Lake event is one subglacial sheetflood, thought to have occurred during the Late Wisconsinan glaciation in Alberta. Rains et al. (1993) proposed that large areas of Alberta, effectively devoid of glaciogenic sediment, reflect erosion by this flood. Their hypothesis proposed that floodwater passed through Alberta, bifurcating around topographically high regions which set up interference zones at downflow floodpath confluences. During episodes of peak discharges, shallow water overtopped these high areas, only partly removing existing sediment. In this manner much of the glaciogenic material was stripped off the landscape, leaving hummocky terrain as slightly modified, locally high areas, often with superimposed, younger, eskers (Shaw et al. 1996). As the flood discharge waned, the sheetflow progressively channelized and diverted eastward, more in conformation with the regional topographic slope (Sjogren and Rains 1995).

The purpose of this dissertation is to test the subglacial flood hypothesis in east-central Alberta in an area that would have been significantly affected by the Livingstone Lake event. If this hypothesis is to be accepted as an alternative to traditional models of subglacial landscape evolution, pertinent erosional and depositional evidence should be present in areas adjacent to the main flow paths. The northern part of the Viking Moraine provides an excellent opportunity to test this hypothesis because the array of glacial landforms has been used to infer stagnating glacial ice and to establish a chronology of ice-frontal positions (e.g., Warren 1937; Bretz 1943; Bayrock 1955; Stalker 1977).

Study Area

Location

The study area is located southeast of Edmonton near the Alberta-Saskatchewan border (Figure 1.1), bounded by 52° - 54° N latitude and 110° - 114° W longitude. This area is within the Alberta Plain physiographic region and lies between approximately 500 and 900 m asl. The region gently slopes from the southwest to northeast.

Bedrock Geology and Preglacial Drainage Systems

The bedrock exposed in the area is Campanian (Upper Cretaceous) to Paleocene (Tertiary) in age (Figure 1.2). The predominantly clastic sediments are poorly consolidated and represent terrestrial and marine deposition in a series of transgressive/regressive cycles of an epeiric sea. The lowest exposed bedrock unit, the Lea Park Formation, consists of fine-grained, dark grey to brown mudstone and siltstone (Rosenthal et al. 1984, cited in Mossop and Shetsen 1994). The upper contact of these marine sediments is gradational with the coarser clastics of the Belly River Formation which reflect initial pulses of sediment resulting from the Laramide Orogeny (Dawson et al. 1994). The Belly River Formation is fluvial in origin and light grey to buff, medium- to fine-grained sandstone and siltstone with minor coal (Dawson et al. 1994). A subsequent transgression of the inland sea (Bearpaw Sea) deposited the Bearpaw Formation that consists of dark- to brownish-grey shale and fine- to medium-grained sandstone, with occasional ironstone concretions (Maslowski-Schutze et al. 1986). As the Bearpaw Sea retreated, a second coarse clastic wedge prograded. The terrestrial Horseshoe Canyon Formation consists of interbedded sandstone, siltstone and mudstone with significant coal seams (Shepheard and Hills 1970) and was followed by a period of relatively limited sedimentation. Sediments deposited at this time make up the Whitemud and Battle formations which consist of white, kaolinitic siltstone (Whitemud) and dark grey shales (Battle) of uniform thickness (10 m) (Dawson et al. 1994). The Scollard Formation, representing a less prominent wedge of terrestrial sedimentation from the Rocky Mountains (Mack and Jerzykiewicz 1989), lies unconformably on the Battle Formation. The Scollard Formation consists of grey to buff sandstone and siltstone, interbedded with olive green mudstone with some coal occurrences (Dawson et al. 1994). Renewed tectonic activity in the early Tertiary (Paleocene) led to the deposition of the Paskapoo Formation which consists of buff coloured sandstone deposited in thick, tabular beds (Dawson et al. 1994).

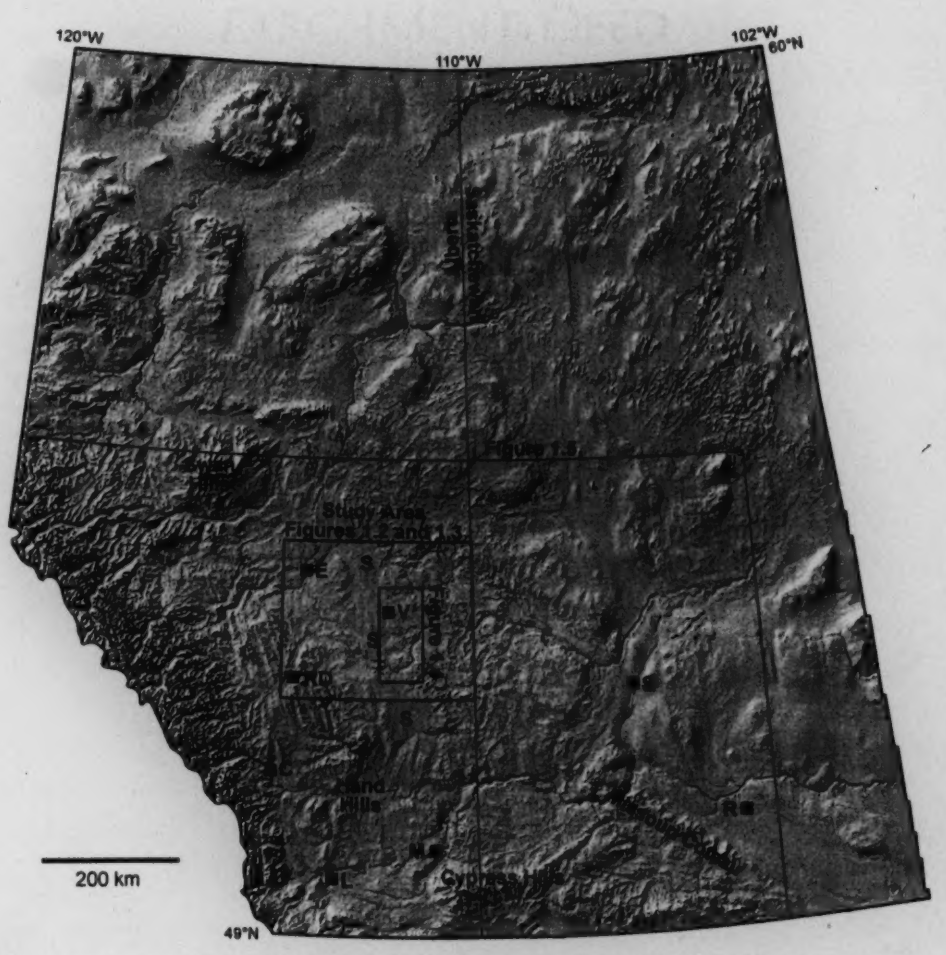


Figure 1.1: Lambertian hillshade model showing the location of the study area in east-central Alberta. Note the sinuous path (S) through the middle of the study area that forms the separation between the Buffalo Lake and Viking Moraine systems.

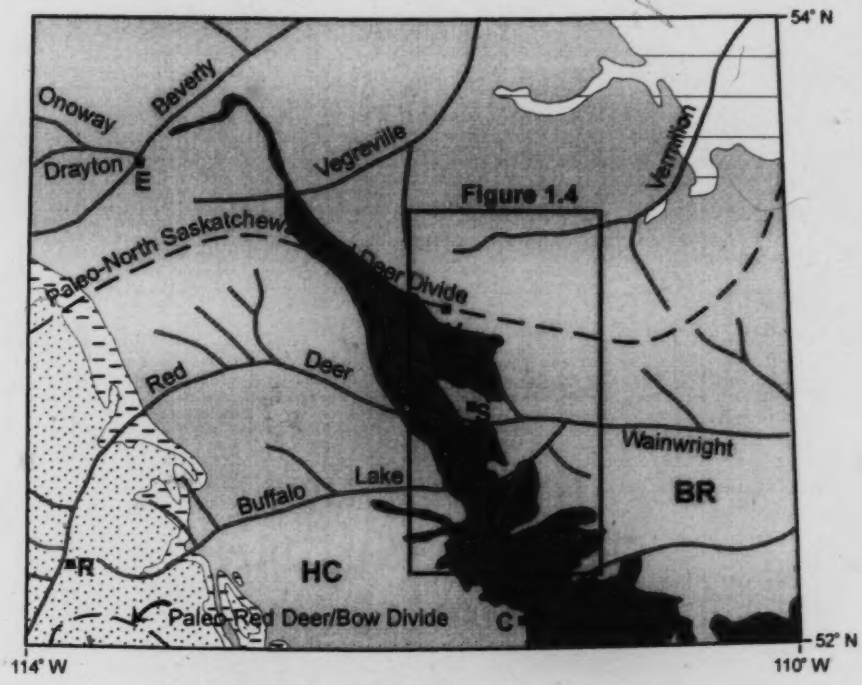


Figure 1.2: Bedrock formations and preglacial valleys. Bedrock formations modified from Jackson et al. (1981). Preglacial valleys modified from Pawlowicz and Fenton (1995). The study area is underlain by bedrock that represents a series of marine transgressions/regressions in the Upper Cretaceous. The preglacial valleys and plain levels are Late Tertiary to Early Quaternary in age and are deeply incised into the poorly consolidated bedrock.

After deposition of the Paskapoo Formation, continued tectonic uplift resulted in fluvial incision from Eocene to Pleistocene time. Planation of preexisting bedrock is recorded by four Cenozoic erosional surfaces (Alden 1932). Warren (1939) suggested that the incision occurred in cycles where incision was followed by periods of aggradation. These cycles are reflected by the different levels in the plains and the gravel caps on uplands such as Cypress, Hand and Swan Hills (Figure 1.1). Inset into the lowest plain level, incised valleys, partly filled with gravels, are present (Figure 1.2). The gravels preserved in these valleys are preglacial, based on the absence of Canadian Shield clasts. These deposits were called the Saskatchewan Gravels and Sands and the presently accepted criteria for identifying them were established by Stalker (1968). Gravels and sands that are below the lowest till have also been called the Empress Formation, but this definition also includes subtill fluvial sediments that contain shield clasts (Whitaker and Christiansen 1972). The presence of these preglacial valleys and their gravel fills must have had important impacts on the dynamics and hydrology of the Laurentide ice sheet. Large, broad, preglacial valleys provided some of the conditions necessary for glaciotectonic displacement of Cretaceous bedrock (Fenton and Andriashek 1984) and highly permeable gravels probably allowed for rapid drainage of meltwater (*cf.* Boulton et al. 1994). Preglacial valleys in the study area include those that comprise the paleo-Red Deer River and paleo-North Saskatchewan River drainages (Figure 1.2).

Glacial Geomorphology

The Viking Moraine trends north-south through the study area, arcing eastward into Saskatchewan at approximately 52° N (Figure 1.3). To the west the Cooking Lake and Buffalo Lake moraines roughly parallel the Viking Moraine, separated by a gently undulating plain, relatively devoid of glaciogenic sediments (Figures 1.1 and 1.3).

Margins of the Viking morainal complex are sinuous in plan and usually gradational with adjacent zones of undulating terrain. Local relief is approximately 10-20 m, greater where large glaciofluvial channels cross-cut the moraine. Hummocky topography dominates the landscape and is interspersed with moraine plateaux and prairie donuts, imparting a spatial zonation of hummocky landforms. "Buried channels"/"stream trenches", eskers, fluting/remnant ridges, glaciolacustrine flats, and glaciotectonized terrain are interspersed, producing discontinuous belts of hummocky terrain. Flagstaff Hill and the Neutral Hills, and other glaciotectonized hills, are present throughout the Viking Moraine (Figures 1.3 and 1.4). These prominent hills are composed of imbricate slabs

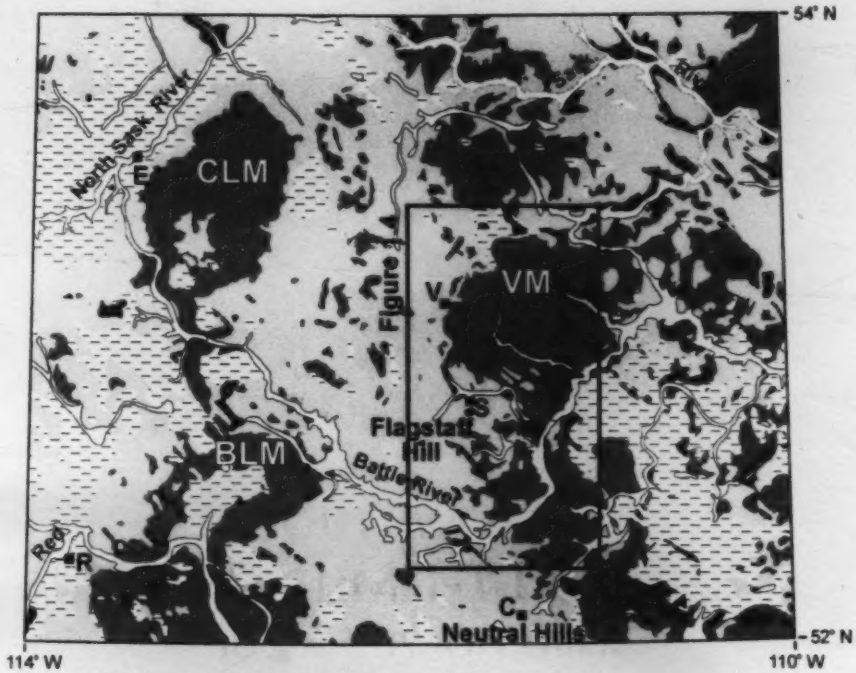
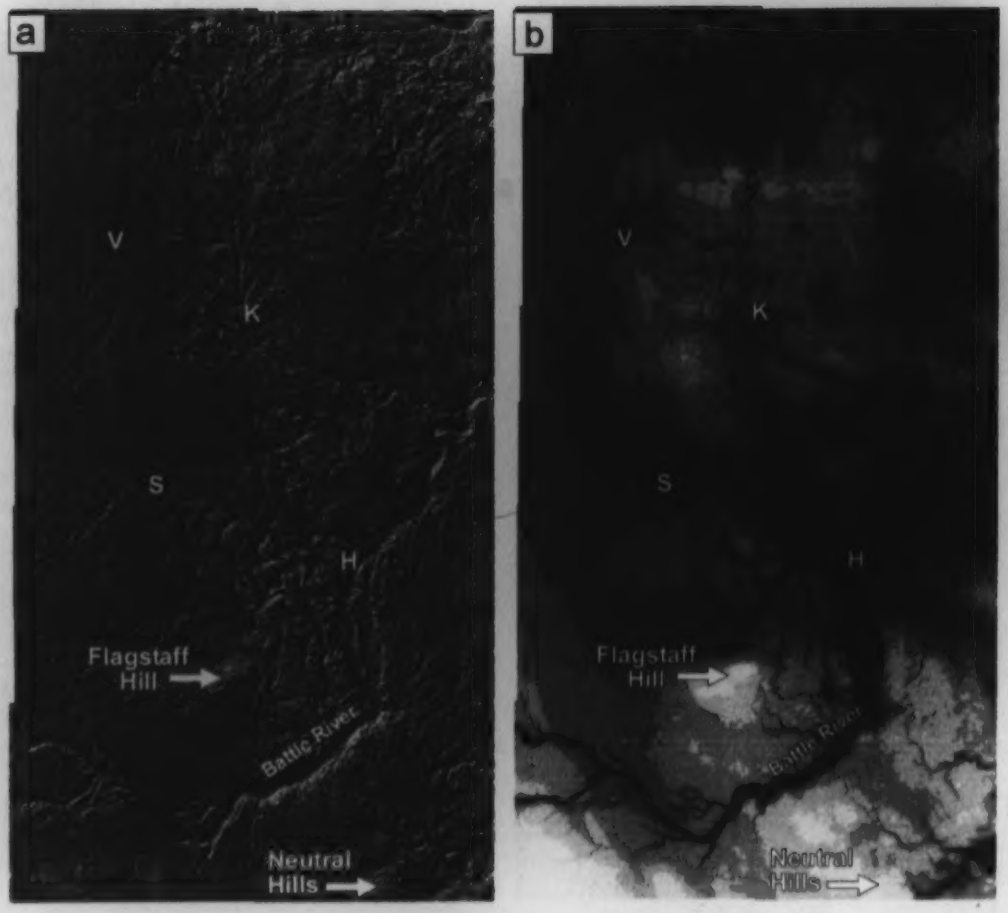


Figure 1.3: Surficial deposits. The Viking Moraine (named after the town of Viking along its western margin) is paralleled by the Cooking Lake and Buffalo Lake moraines to the west. Reentrants in the moraines usually contain lower relief hummocky topography and the glaciofluvial sediments are inset into the higher relief hummocks.



H-Hardisty, K-Kinsella, S-Sedgewick, V-Viking

Figure 1.4: Eastern margin of the Viking Moraine. (a) Lambertian hillshade model. (b) Classed elevation. Note the Viking upland (subtle upland east of the town of Viking above 700 m asl) is separated from higher ground near Flagstaff Hill by a sweeping trough from Viking to Sedgewick.

of local bedrock, occasionally mantled with glaciogenic sediments.

The Viking Moraine: previous research

One of the first scientific accounts of this area was by Tyrrell (1887) who surveyed the major rivers and tributaries, and although primarily concerned with the bedrock geology he included some descriptions of the surficial deposits. Warren (1937) was the first to seriously investigate the significance of the morainal area that he termed the Viking Moraine after the town of Viking located along the feature's northwest periphery (Figure 1.5). Warren (1937), prompted by the tentative conclusion that the moraine along the Missouri Coteau represented the Late Wisconsinan glacial maximum (Johnston and Wickenden 1931), laid the groundwork for interpreting morainal systems in Alberta, west of the Missouri Coteau. Warren (1937) tentatively proposed that the Viking Moraine represented a terminal glacial position, prior to the Late Wisconsinan glaciation, based on the subdued topographic expression in comparison to the Coteau Moraine in Saskatchewan. Rutherford (1941) questioned this age and suggested that moraines in Alberta represent lateral rather than terminal positions. He based this interpretation on the probability of postglacial tectonic uplift in the south, thus creating a south to north decrease in elevation of Keewatin moraines in western Alberta. Bretz (1943) provided the first detailed study of glacial meltwater channels for the purpose of correlating ice frontal positions in Alberta and Saskatchewan. He noted that the Viking Moraine failed to conform to the map of Warren (1937) and concluded that it represented an Early Wisconsinan advance and the Coteau Moraine was Late Wisconsinan. Warren (1954) formalized the Viking Moraine by defining it as "a series of moraines lying west of the Coteau moraine and east of the Torlea Flats".

The Torlea Flats form a gently rolling plain separating the Buffalo Lake and Viking Moraine systems. The subtle topographic expression of this plain reflects the underlying bedrock that is intermittently mantled by a thin veneer of glaciogenic sediment. Where preglacial valleys exist, thick preglacial gravels and sands are present. Warren (1937) suggested that the paucity of glaciogenic material in this area indicated that a long period of erosion had elapsed between the deposition of the Buffalo Lake and Viking Moraine systems. Gravenor and Bayrock (1955) attributed the flatness of the plain to the underlying bedrock (Bearpaw shales) and to increased sliding (and limited deposition) due to packing of basal ice with bentonitic clays derived from the bedrock. Rains et al. (1993) suggested that the paucity of glaciogenic material in this area was due

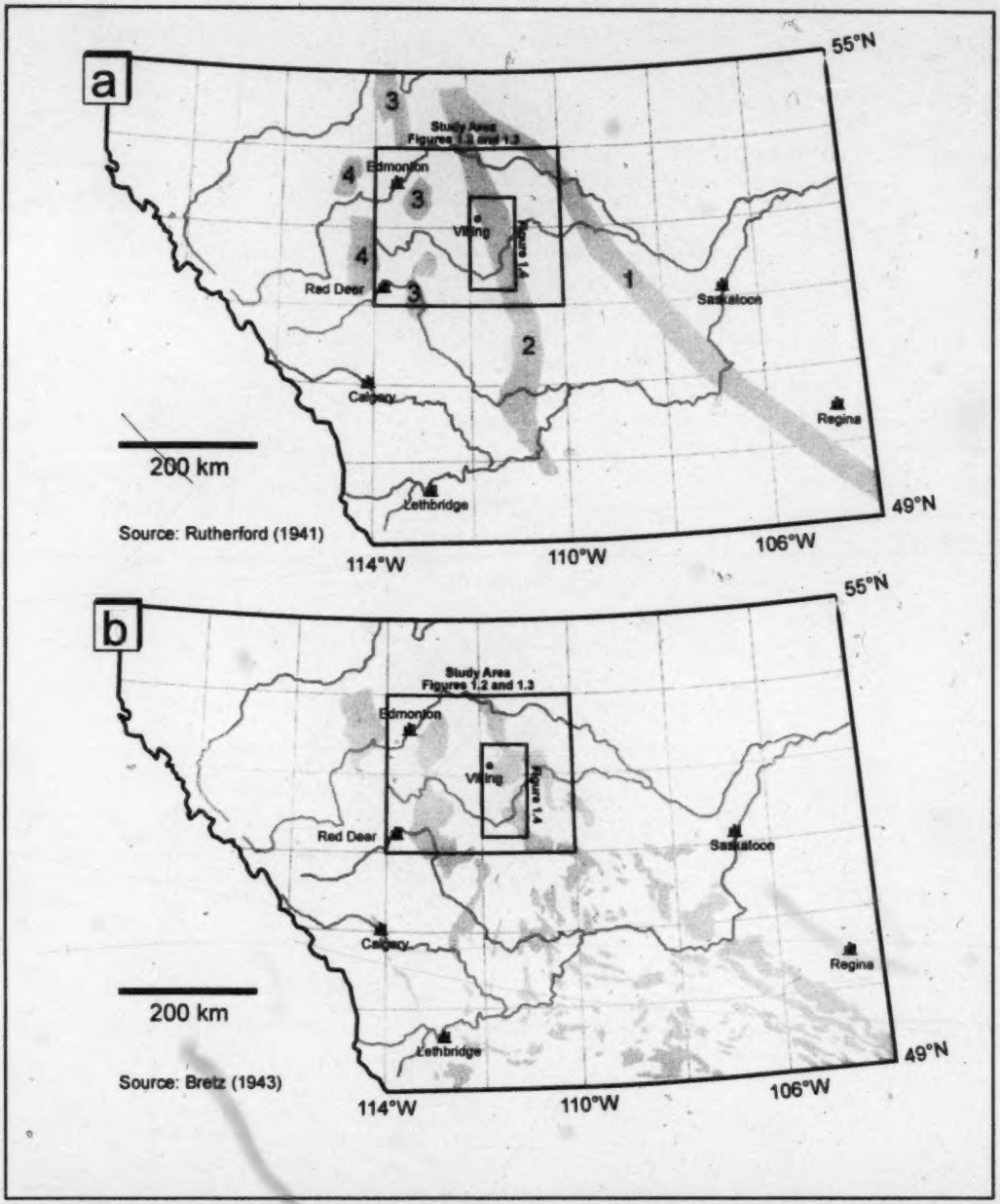


Figure 1.5: Classical interpretations of morainal complexes on the Canadian prairies. (a) Rutherford's (1941) interpretation of four glacial moraines, 1 = youngest (Altamont) to 4 = oldest. (b) Bretz's (1943) map of the same moraines shows a more realistic pattern of discontinuous morainal systems. Note that the basis for establishing the increasing ages between the Viking and Buffalo Lake Moraines was the more subtle expression for the older (Buffalo Lake) and their separation by a relatively till-free zone (Torlea Flats).

to erosion by subglacial meltwater sheetfloods that were also responsible for the formation of hummocky terrain and remnant ridges that are associated with the area. Sjogren and Rains (1995) extended this argument by illustrating that progressive channelization of a subglacial meltwater sheetflood was responsible for anabranched channel systems incised into the Torlea Flats in the Coronation area.

Questions to be addressed by this dissertation

The main objective of this dissertation is to determine, on the basis of empirical data and available glaciologic theory, the origin of the Viking Moraine. Testing available theories of individual landform formation and critically evaluating each in the context of one region will establish their validity. Inductive reasoning will be used to extrapolate from the formation of individual landforms to the probable formative environments for the moraine in general. This will be accomplished by investigating landform/sediment associations and also the regional landform context. To arrive at a generalized model of glaciation and deglaciation in the region several specific questions must be addressed:

1. What process(es) are responsible for the large-scale landscape unconformities in east-central Alberta?
   a. Do the large areas that are largely devoid of glaciogenic sediments represent erosion by ice streams, catastrophic floods of subglacial meltwater, and/or non-deposition by the Laurentide ice sheet?
   b. What landform/sedimentary evidence for these processes is present in these areas?
   c. How does the formation of the Torlea Flats relate to the formation of the northern part of the Viking Moraine.

2. What environment(s) are represented by meltwater channels, and more specifically, "stream trenches" that dissect the Viking Moraine?
   a. Do the "buried channels" represent subaerial glaciofluvial processes (ice marginal and/or proglacial) or is it probable that at least initial formation was subglacial with later subaerial modification? Do channel morphology, sediments and the topographic setting support formation in ice-walled channels within stagnant ice? Are the "stream trenches" polygenetic? What can superimposition and cross-cutting relationships between the complex of "stream trenches" tell us about the sequence of channel formation, and the character of deglaciation in the area?
   b. Were other glaciofluvial channels in the region contemporaneous with the "stream trenches"? Do the changes in channel morphology represent variations in drift thickness, paleohydraulic conditions, bedrock lithology and/or glaciological control? Was the formation of these channels contemporaneous with the "stream trenches"?

3. What depositional environment(s) are represented by the gravel and sand in the Kinsella basin? How does the geomorphology and sedimentology of this basin fill relate to the glacial features that constrain its extent? Do the sediments represent "normal" outwash during deglaciation, subglacial sedimentation and/or a combination of the two? How does the timing of this deposition relate to the cutting of the "stream trenches", found immediately adjacent to the basin?

4. What was the formative environment for the hummocky terrain that dominates the Viking Moraine?

   Is there evidence for regional stagnation and a supraglacial evolution of the hummocky terrain? What can be said about the hummock sediments; is there evidence of debris flows, lacustrine sedimentation, glaciotectonics, and do these sediments suggest sub- or supraglacial origin? Does the sedimentary architecture indicate that the hummock morphology is primary or is the form independent of deposition? Are there consistent architectural themes between hummocks throughout the region or do localized processes appear to have been dominant? Can the morphology and associations of hummocks with other landforms be used to infer timing and environment of formation of the hummocky terrain?

Thesis Organization

This thesis is presented in six chapters. Chapters One and Six contain the introduction and regional synthesis respectively. The remaining chapters are presented in an order that emphasises the regional significance of the topic. Chapter Two focuses on regional-scale, erosional patterns adjacent to the Viking Moraine, inferred from terrain models and field reconnaissance. Implications for regional-scale subglacial landscape evolution are discussed and the regional setting is established for subsequent chapters. Chapter Three investigates the erosional and depositional characteristics of meltwater channels that dissect the Viking Moraine. Channel morphology and landform associations are used to infer probable polygenesis for these channel networks. Chapter Four links morphological and sedimentological characteristics of glaciofluvial basin fill in the Kinsella area. The sediments of the basin fill are used in conjunction with associated landforms to infer the formative environment. Chapter Five links the morphology and the sedimentology of hummocky terrain into a generalized model of hummock formation in this area. Chapter Six summarizes the findings of the earlier chapters and proposes several future research objectives.

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CHAPTER TWO: REGIONAL-SCALE, EROSIONAL LANDFORMS AND SUBGLACIAL HYDROLOGIC REORGANIZATION OF THE SOUTHWESTERN LAURENTIDE ICE SHEET: EVIDENCE FROM EAST-CENTRAL ALBERTA.

Introduction

Ice sheet dynamics are greatly influenced by the topography of the ice sheet and its bed, the geological/rheological character of the substrate, and glacial hydrology. The surface topography of an ice sheet is responsible for glacier flow, whereas the importance of bed topography for routing flow and/or ice streams increases with the amplitude of roughness elements compared to the thickness of the ice sheet. Marshall et al. (1996) used several landform and geological parameters to model probable zones of fast flow (ice streams) in the Laurentide ice sheet, stressing the importance of meltwater routing. Similarly, Arnold and Sharp (1992) suggested that the introduction of glacial hydrology into an ice sheet model resulted in a marginal zone characterized by rapid sliding, thin ice, and low surface slopes. Shoemaker (1992a) suggested that episodic subglacial floods resulted in low-relief ice sheet profiles. This hypothesis is particularly important for the southwestern part of the Laurentide ice sheet because low surface gradients have been inferred from geological evidence (Mathews 1974; Rains et al. 1990; Jackson et al. 1996). The significance of the subglacial hydrology in the evolution of ice sheets has been linked to the production of high water pressures, within deforming beds and/or at the ice-bed interface. The following fundamental questions arise: (1) to what extent does subglacial meltwater drainage occur through the substrate and/or along the ice-bed interface? (2) what is the geometry of flow (i.e. channel or sheetflow)? and (3) is meltwater drainage steady state or catastrophic in nature?

The ability of water to drain through the substrate is dependent on the pressure head and the nature of the substrate. Boulton et al. (1995) suggested that the transmissivity of large aquifers was sufficient to drain glacial meltwater because the flow fields were reorganized. In the absence of major aquifers, water would be discharged at the ice-bed interface in conduits. In direct contrast with Boulton et al. (1995), Alley (1989) suggested earlier that the capacity of subglacial aquifers to transmit meltwater was generally less than the amount produced, thereby creating high water pressures at the ice-bed interface. Meltwater may be discharged along the ice-bed interface as sheetflow or channelized flow. Rothlisberger (1972) and Weertman (1972) provided the theoretical basis for channelized flow and sheetflow (film), respectively. Thin films or sheets of water are inherently unstable because lateral pressure gradients lead to channelized flow (Walder 1982), though there is some indication that there may be oscillatory behaviour between these two flow types

(Weertman and Birchfield 1983). Most discussions on the stability of sheetflow at the ice-bed interface have focussed on hard bed (impermeable) conditions. The introduction of permeable, subglacial sediments presents two problems. First, how is the meltwater flow partitioned between that flowing at the ice-bed interface and through the substrate? Second, how are conduits kept open if glacier ice and sediment are deforming into the conduit? Boulton and Hindmarsh (1987) and Alley (1992) addressed this problem and suggested that conduit maintenance in deformable sediment is related to the delivery of sediment to the conduit, and the rate of removal, in addition to the rate of deformation of ice into the conduit. Alley (1992) showed that the distance from which deforming sediment can reach the conduit is limited by the yield strength. Walder and Fowler (1994) suggested that channelized flow in areas with deformable beds will not occur as classic R- or N-channels (R - cut up into the basal ice, N - cut into the substrate) as in areas with impermeable sediment. Rather, channel geometry is dependent on the effective pressure. High and low pressures are characterized respectively by sediment-floored R-channels and shallow canals cut into the substrate. The delicate balance between the deformation of ice and sediment in controlling the geometry of meltwater drainage is dependent on steady-state drainage. Many of the physical controls are superceded, at least temporarily, when catastrophic drainage occurs faster than the ice/sediment system can adjust.

Subglacial sheetfloods of meltwater have been invoked to explain observations of landforms and sediment packages throughout the southern and western portions of the Laurentide Ice Sheet. The strongest evidence for massive subglacial sheetfloods is the regional continuity of erosional and depositional landforms. Shape similarities between erosion marks formed by turbulent flows at various scales, and drumlins in northwestern Saskatchewan, were the original impetus for this hypothesis (Shaw 1983). Subsequently, several papers have stressed the linkage between erosion marks, known as p-forms (Dahl 1965) or s-forms (Kor et al. 1991), and regional scale sheetfloods (e.g., Shaw 1988, 1989; Tinkler and Stenson 1992). Rogen moraine (Fisher and Shaw 1992), tunnel channels (Brennand and Shaw 1994), flutes/remnant ridges (Shaw 1994), elongate lakes (Gilbert and Shaw 1994), hummocky terrain (Rains et al. 1993; Munro et al. 1996; Munro and Shaw 1997), and channelled scabland (Sjogren and Rains 1995) have also been attributed to catastrophic subglacial floods of meltwater. The ability to explain assemblages of morphologically different landforms by one mechanism has made this hypothesis attractive. Landform variations can be explained by changes in turbulent flow structures, controlled largely by the geometric relationship between the ice roof and substrate. The geometric relationship between ice sheet slope and bed slope was investigated by Shoemaker (1992b) in an attempt to model the initiation and termination of

subglacial outburst floods. Locally, geometric configuration of the ice and bed controlled flow velocities (and routing) and therefore influenced the location of glacial landforms such as eskers, tunnel channels/valleys (Brennand and Shaw 1994), and hummocky terrain (Rains et al. 1993). Although the subglacial sheetflood hypothesis appears to satisfactorily explain many otherwise enigmatic landform characteristics, it meets with considerable scepticism in the scientific community, despite the large amount of supporting field evidence documented in the literature since 1983 (Benn and Evans 1998).

Study Area

The study area is roughly bounded by 110°-114° W longitude and 51°-54° N latitude (Figure 2.1). This area straddles the terrain between the Viking and Buffalo Lake moraines in central Alberta (Figure 2.2). The two morainal belts are separated by a zone, relatively free of glacial sediment, called the Torlea Flats (Warren 1937). Warren (1937) stated that the character of this area resulted from to removal of glaciogenic material (interglacial erosion) leaving a relatively flat plain largely controlled by the underlying bedrock. Gravenor and Bayrock (1955) suggested that the near-absence of glacial material in this zone was the result of enhanced glacial sliding and nondeposition. Alternatively, Rains et al. (1993) suggested that the paucity of glaciogenic sediments in this and similar areas in Alberta resulted from subglacial meltwater erosion. They showed that the distribution of solonetzic soils, derived postglacially from the underlying saline bedrock, coincides closely with areas of 'draped moraine' or 'weakly developed hummocky topography' indicated in the landform zonation mapped by Shetsen (1987, 1990) (Figure 2.2).

Rains et al. (1993) hypothesized that at least one large subglacial flood (Livingstone Lake event) passed across much of Alberta, creating large tracts of hummocky terrain, scoured bedrock, and giant flutings/remnant ridges. These observations from Alberta were subsequently connected to extraglacial pathways (Shaw et al. 1996) where meltwater exited into the Gulf of Mexico via the Mississippi valley. Rains et al. (1993) and Shaw et al. (1996) indicated that two main flow paths in Alberta bifurcated and rejoined, forming an anabranched pattern, with secondary linkages. This paper will illustrate the relationships between landforms within, and immediately adjacent to the proposed eastern flow path, which is roughly equivalent to the Torlea Flats in the study area (Figure 2.2).

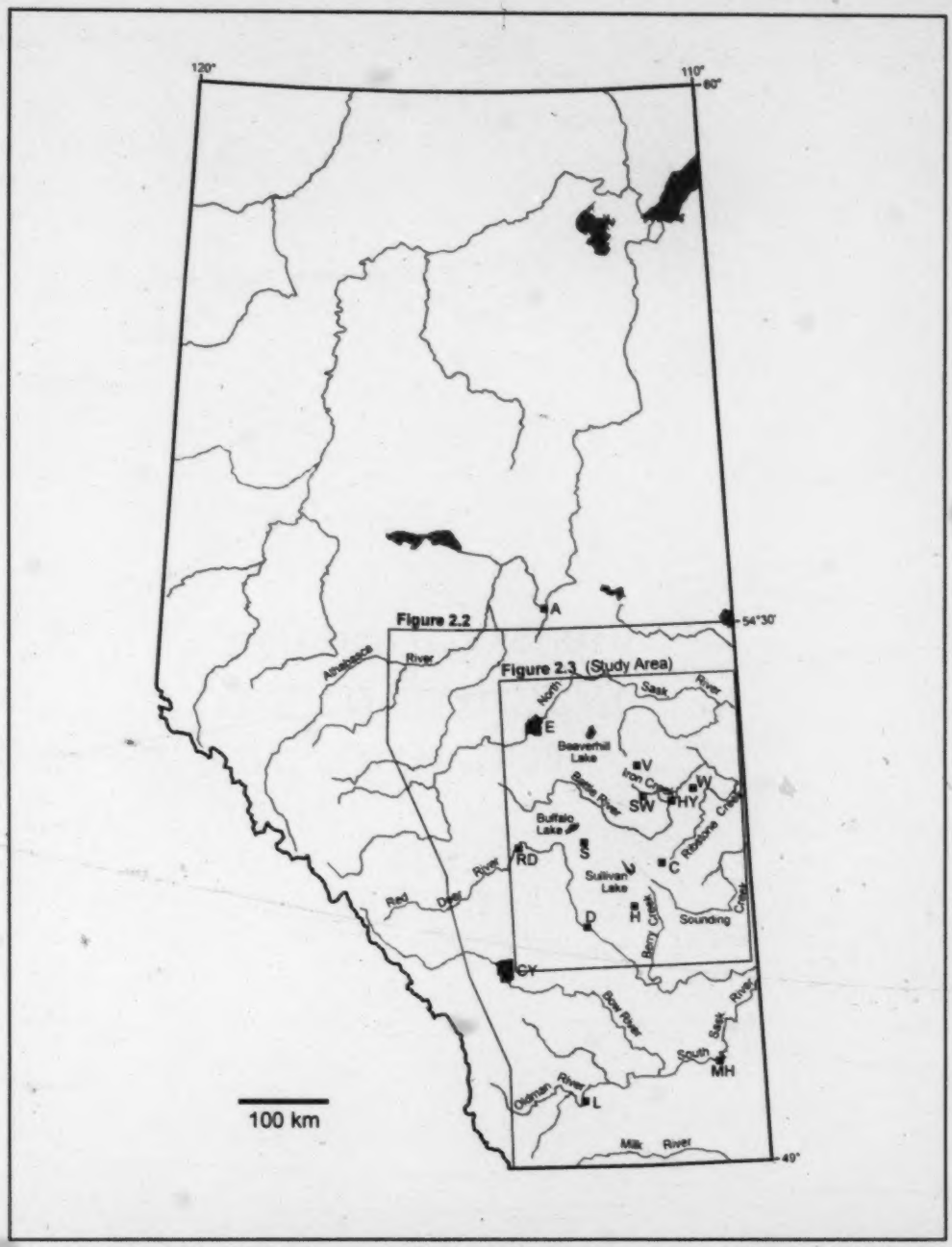

Figure 2.1: Location of the study area and features of interest in east-central Alberta. A-Athabasca, C-Coronation, CY-Calgary, D-Drumheller, E-Edmonton, H-Hanna, HY-Hardisty, L-Lethbridge, MH-Medicine Hat, RD-Red Deer, S-Stettler, SW-Sedgewick, V-Viking, W-Wainwright.

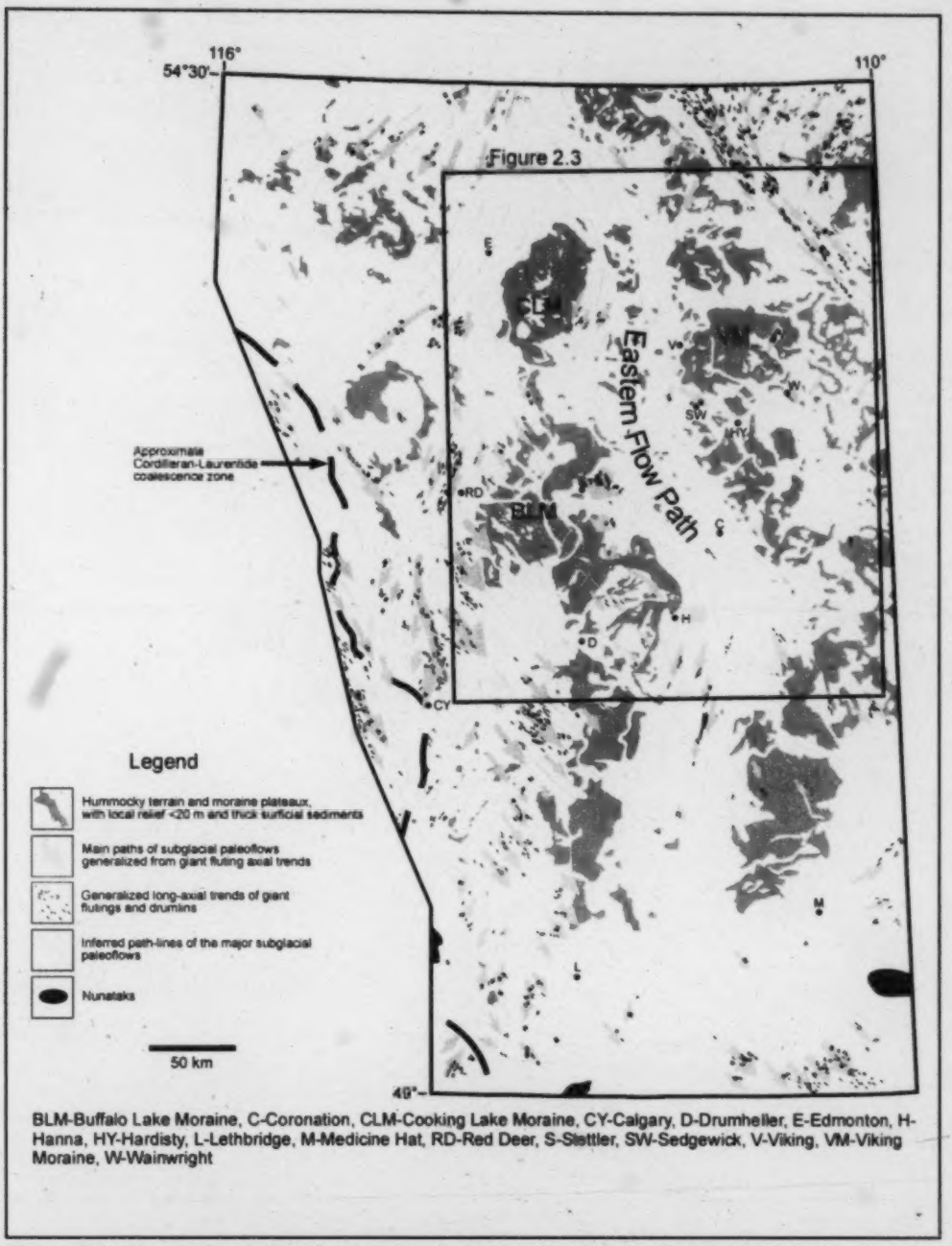
116°
54°30'
110°
49°
Figure 2.3
Eastern Flow Path
Approximate Cordilleran-Laurentide coalescence zone
Legend
Hummocky terrain and moraine plateaux, with local relief <20 m and thick surficial sediments
Main paths of subglacial paleoflows generalized from giant fluting axial trends
Generalized long-axial trends of giant flutings and drumlins
Inferred path-lines of the major subglacial paleoflows
Nunataks
50 km
BLM-Buffalo Lake Moraine, C-Coronation, CLM-Cooking Lake Moraine, CY-Calgary, D-Drumheller, E-Edmonton, H-Hanna, HY-Hardisty, L-Lethbridge, M-Medicine Hat, RD-Red Deer, S-Slattler, SW-Sedgewick, V-Viking, VM-Viking Moraine, W-Wainwright

Figure 2.2: The configuration of major morainal zones in southern Alberta. Superimposed on this morainal pattern are the flow lines of the Livingstone Lake subglacial outburst flood. The flow lines show complex anabranching patterns, inferred from the axial trends of flutings/remnant ridges. Modified from Rains et al. (1993).

Terrain Modelling

Large landforms, such as those presented in this paper, have often been overlooked, primarily because conventional techniques such as aerial photograph and satellite image interpretation are limited by the scale of the photography, reflectance properties of the surface, and to a lesser extent topography. This is more apparent when large features are to be mapped because aerial photographs may not cover the entire landform and, thus, may be missed by the interpreter. The texture of satellite imagery, imparted by cultural features, overpowers subtle changes related to extremely large landforms. Even with these limitations, satellite imagery has proven useful for mapping glacial landforms (e.g., Punkari 1985; Boulton and Clarke 1990; Clarke 1993). Aquisition of low-sun angle, Landsat (MSS) imagery has been successful for delineating subtle, large landforms when the topography was snow-covered (Eyton 1989; Skoye and Eyton 1992). One limitation of mapping from optical satellite imagery is that the viewing and lighting geometries are largely fixed and, therefore, coincidence of landform trend is necessary for detection. Some of these limitations are avoided when the interpreter uses terrain models for landform mapping. By simulating lighting angles it is possible to visualize landforms, without the overprint of cultural features, by producing shaded maps. Hillshade models allow the interpreter to visualize landform morphology in the absence of vegetation and cultural features.

Two data sources were used in this paper: (1) Digital Terrain Elevation Data (DTED), obtained from the Products and Services Division, Natural Resources Canada, Ottawa. These data were acquired from secondary sources with 3 arc-second spacing in latitude, 6 arc-second spacing in longitude, and vertical accuracies of ±30 m. They were digitally mosaicked and displayed in a Universal Transverse Mercator projection (UTM) with a ground resolution of 200 m. (2) DEM data were obtained from the Alberta Government at a scale of 1:20,000. These data were produced with commercial software (SCOP) using direct measurements from stereo, aerial photographs. The 1:20,000 DEMs were sampled at 25 m and have vertical accuracies of ±3 or ±5 m, depending on the type of vegetation present. Data errors, at the junction of two photo sets, appear as orthogonal edges where the entire adjacent data set is vertically displaced. Other errors in these data are easily picked out as regularly spaced, linear edges or regular patterns of "dimples". These terrain models are displayed in a UTM projection with a ground resolution of 50m.

Observations

Regional-Scale Oriented Landforms

There is a continuum of linear, glaciogenic landforms, ranging from small, subtle features with wavelengths measured in metres, to those measured in kilometres (*cf.*, Clarke 1993). Individual flutings/remnant ridges are commonly indicated by a single symbol on surficial geology maps, thereby masking their topographic and morphologic variability that exists. Most linear glacial landforms described in the literature are high, relative to their spacing, which facilitates mapping. Many subtle forms are not visible at ground level or in aerial photographs, simply because of extremely small amplitude and/or large areal extent of the landforms. The linear features described in this paper illustrate the scale continuum of flutings/remnant ridges and raise some interesting questions about how these landforms relate to glacial dynamics and hydrology.

Many oriented landforms in east-central Alberta have not been mapped because of their low amplitude and large wavelength. Regional-scale ridges/troughs, found in the Torlea Flats (Figure 2.3), are roughly coincident with the eastern flow path of the hypothesized Livingstone Lake megaflood (Figure 2.2). The Torlea Flats form a nearly continuous feature, sinuous in plan with poorly defined margins. In many locations there is an almost imperceptible transition between the undulatory Torlea Flats and higher, "rugged", hummocky terrain on either side. Constrictions along the length of the "Flats" are coincident with steep margins, that give the appearance of relatively narrow-deep reaches (Figure 2.3) separated by wide-shallow portions. The topography of the "Flats" is provided by the surface of the Upper Cretaceous bedrock, with little glaciogenic material covering it. However, thick glacial sediments are present in preglacial valleys.

The Torlea Flats have undulatory long profiles that run uphill, and parallel or slightly oblique to, the southwest-northeast regional slope (Figures 2.3 and 2.4). The long profile shows a few significant breaks in slope (subtle escarpments) 50-100 m high, superimposed on the uphill regional trend (Figure 2.4). Because the orientation of these incised "Flats" is oblique to the regional slope, transverse profiles show an eastward trend toward lower elevations. Transverse profiles are convex-up, sloping gently to the east, with pronounced secondary undulations in the central part of the flow path that represent broad regional-scale ridges and intervening troughs (Figure 2.4).

The regional-scale ridges/troughs appear as little more than subtle undulations in the landscape with many smaller, superimposed landforms mapped by Shetsen (1987, 1990). The regional-scale oriented landforms are not distinct features but appear in Figure 2.3 as low, broad ridges, separated by shallow, linear troughs. The outlines of these forms are indistinct partly because

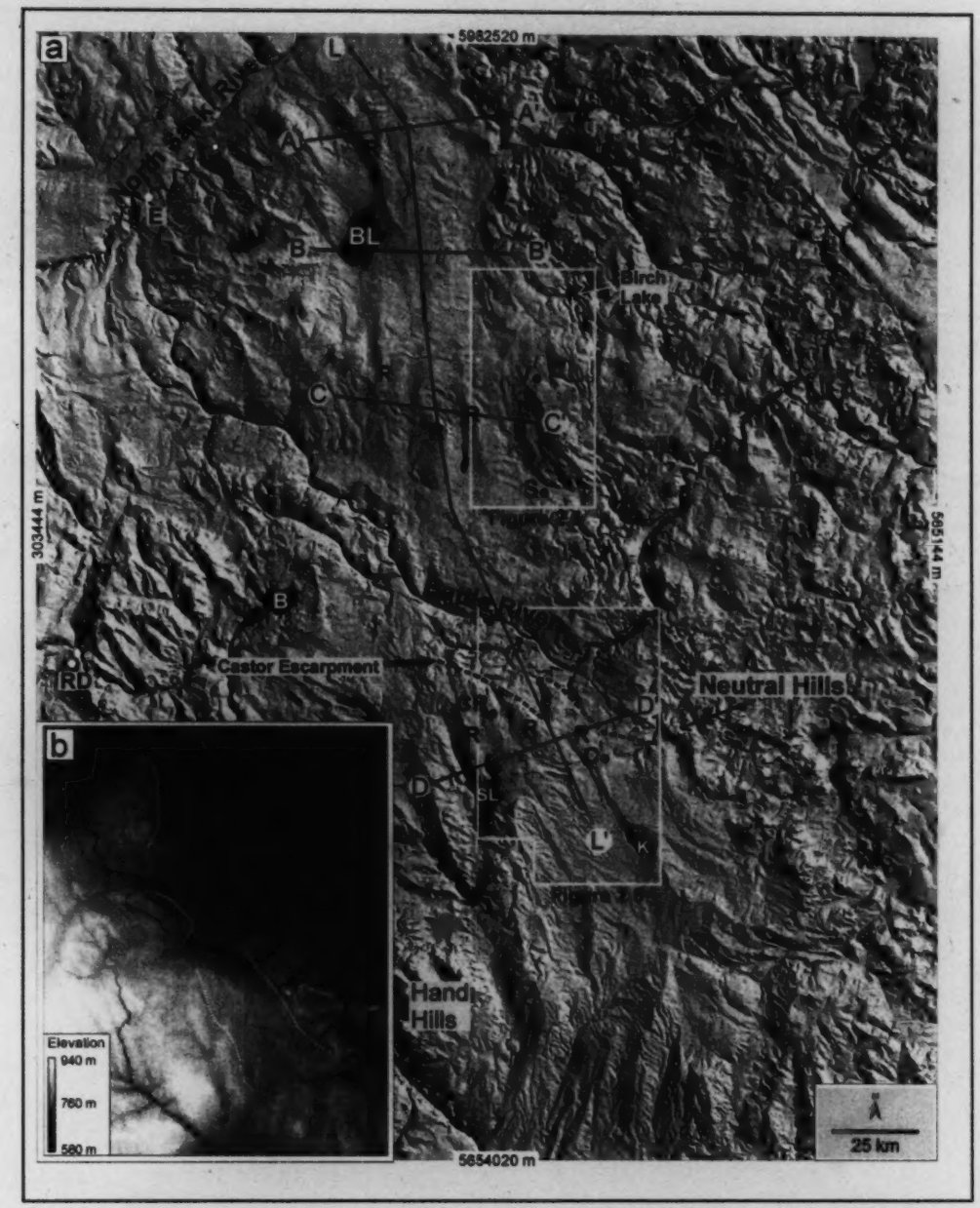

Figure 2.3: The study area in east-central Alberta. (a) Hillshaded relief derived from DTED 3-arc second data projected to a 200 m UTM grid. This model was created using a solar azimuth and angle of 60° and 40°. The locations of profiles in Figure 2.4 and Figures 2.5 and 2.8 are shown. (b) Continuous greyscale map of elevation showing the Torlea Flats as a distinct topographic feature. B-Buffalo Lake, BL-Beaverhill Lake, C-Coronation, CR-Castor, E-Edmonton, K-Kirkpatrick Lake, RD-Red Deer, SK-Sedgewick, SL-Sullivan Lake, V-Viking.

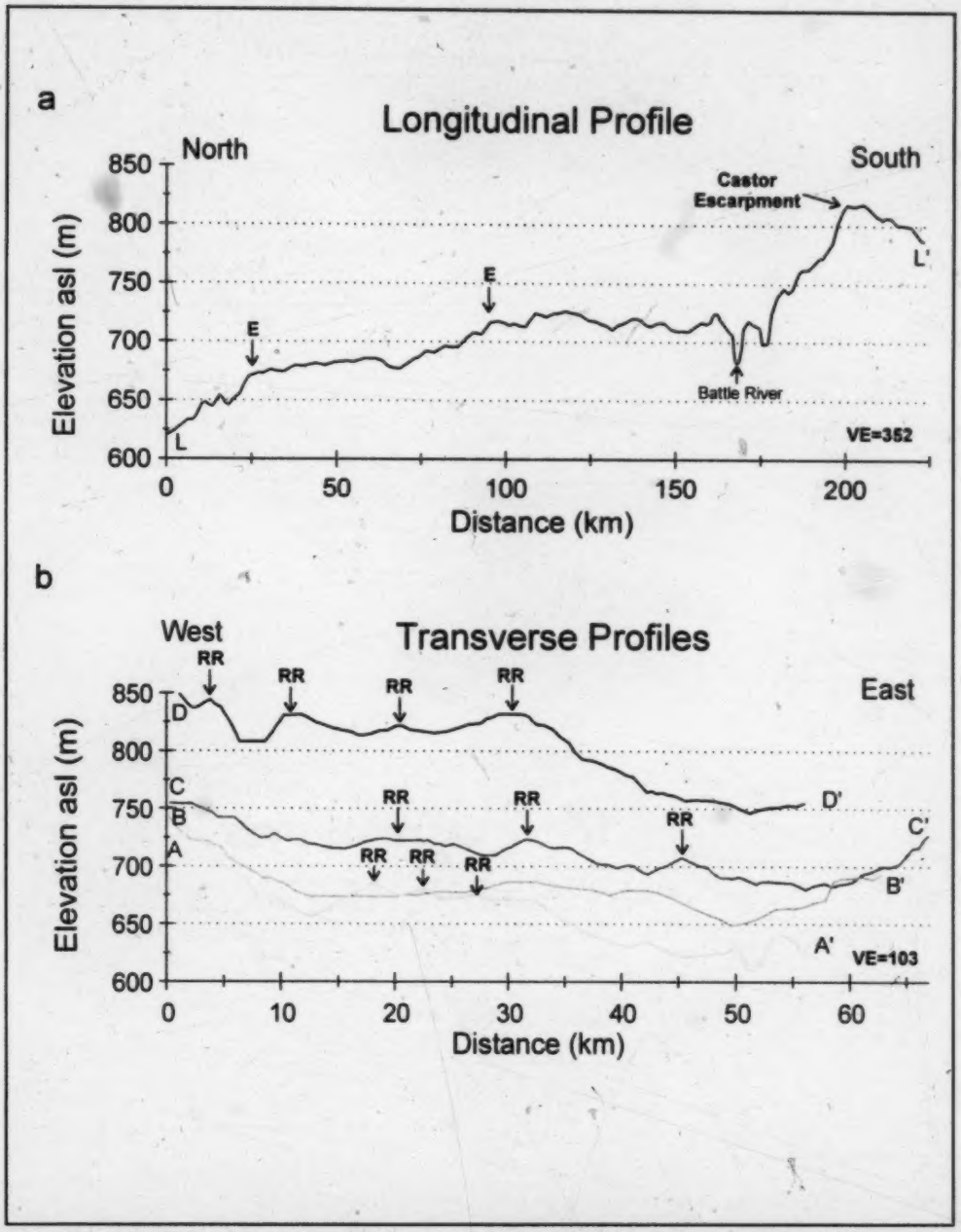

Figure 2.4: Profiles of the Torlea Flats (eastern flow path) derived from the DTED 3-arc second data. See Figure 2.3 for the locations. (a) Longitudinal profile illustrating the generally uphill trend of the Torlea Flats (eastern flow path) and the subtle escarpments (E). (b) Transverse profiles across the Torlea Flats show the amplitude of the regional-scale ridges (RR) and the eastward decrease in elevation.

of the numerous superimposed meltwater channels that trend obliquely off the ridges. The depths of the troughs that flank the regional-scale ridges range from 10 to 25 m, though the elevation difference between the Torlea Flats and adjacent hummocky terrain is often greater than 50-100m. This establishes the regional-scale ridges as features contained within the larger inscribed feature. The largest ridges in Torlea Flats are arranged in linear to curvilinear patterns; ridges adjacent to each other are parallel to divergent. Most ridges have slightly wavy outlines and undulatory crestlines (Figure 2.3), partly due to incision of small postglacial channels. Ridges have v-shaped prows, without crescentic scours, and are discontinuous. They fade out near Beaverhill Lake, but reappear further south where they are aligned nearly north-south. The regional-scale ridges/troughs south of Beaverhill Lake are slightly divergent where features at lower elevations are better defined. Farther south, near the Battle River, a north to northeast-facing escarpment, herein referred to as the Castor Escarpment (Figure 2.4), coincides with an eastward deflection of the regional-scale ridges/troughs. Here the ridges are better developed than farther north and are obliquely dissected by channels of the Coronation-Spondin scabland (Figure 2.3. See also, Sjogren 1993; Sjogren and Rains 1995).

As previously mentioned, landforms at different scales indicate that there was continuity of formative process. The regional-scale ridges/troughs in the Torlea Flats are superimposed by meltwater channels and smaller linear landforms which indicate that topography of the larger features was important in their formation. Most of the landform examples show a general eastward deflection/diversion of the medium that formed the linear features and was routed in response to a topographic influence.

Viking-Sedgewick Area

Superimposed on the large, regional-scale ridges/troughs illustrated in Figures 2.3 and 2.4, are many smaller, linear features oriented at various angles to the larger landforms. Along the eastern margin of the Torlea Flats, scoured bedrock and parallel to divergent, superimposed fluting/remnant ridge fields attest to deflection, diversion, and continuity of the formative process. In the northern part of the study area, linear ridges are present in two settings. First, within the Torlea Flats there are linear ridges which are very subtle. Second, ridges occur in an arcing trough that branches off from the "Flats". In the first setting the ridges have convergent or divergent long axes, depending on their proximity to the hummocky terrain of the Viking Moraine. In the extreme northwestern part of Figure 2.5, broad ridges are oriented north-northwest to south-southeast, and

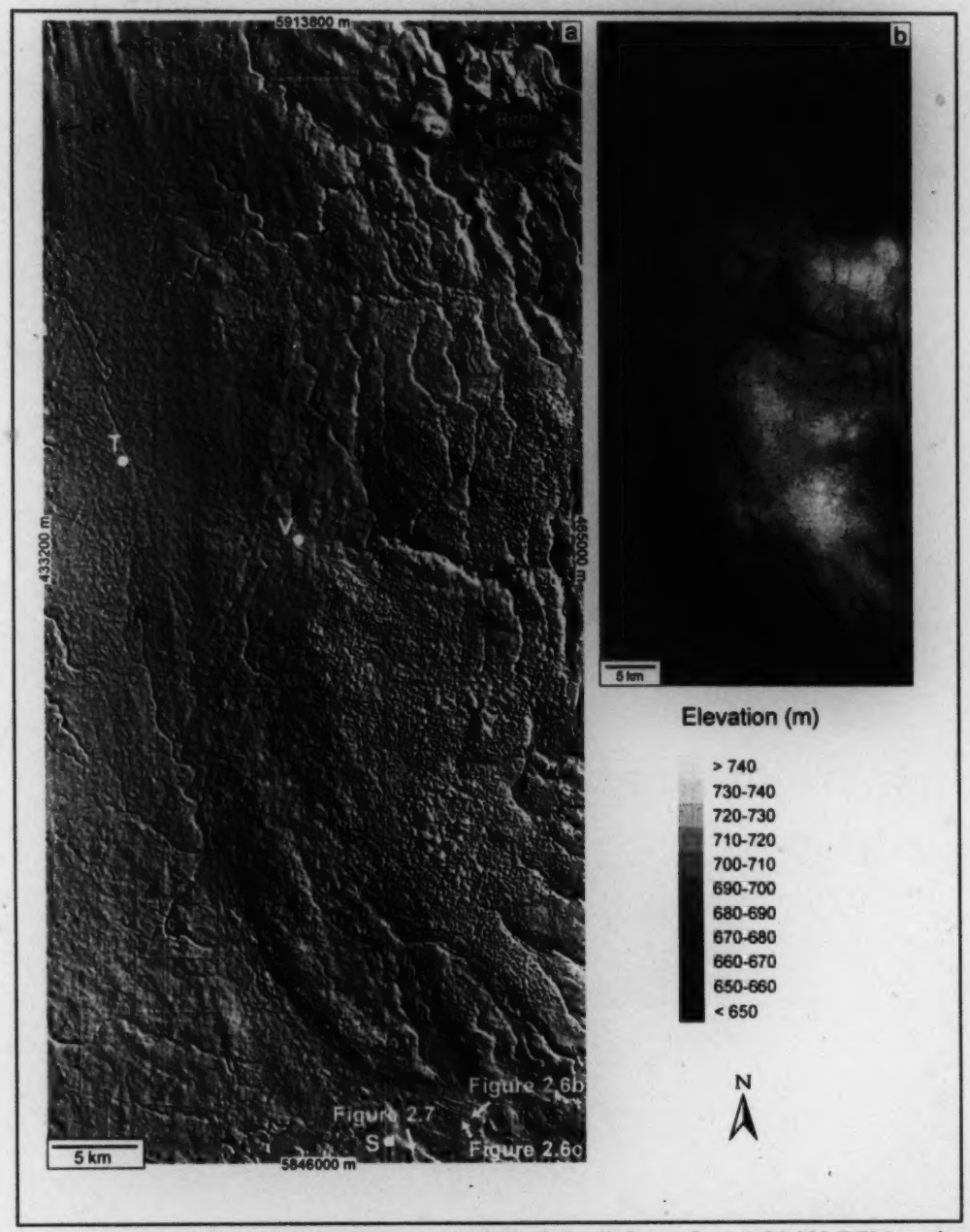

Figure 2.5: The Viking-Sedgewick area. (a) Hillshaded relief map from 1:20,000 DEMs, solar azimuth=60°, angle=40°. Subtle linear ridges (R) occur at different angles in the Viking (V) and Torlea (T) areas and are shown to converge on a trough that arcs through the Sedgewick (S) area and contains well-defined remnant ridges. (b) Classed elevation map showing the topographic context for the subtle ridges shown in (a).

taper to points southward. These ridges occupy the southern extension of a lateral trough that defines the margin of the Torlea Flats. Southwest of Birch Lake, very subtle, linear landforms trend toward the town of Viking (Figure 2.5). These forms are extremely indistinct, accentuated by channel incision in the troughs. The orientation of the linear landforms, along with the glaciofluvial channels, provide a sharp contrast to the oriented features northwest and southwest of Viking. The northeast-southwest oriented elements ornament more subtle forms from the north-northwest where they converge, south of Viking. The linear ridges, trending northeast-southwest, are truncated by sinuous channels that link with Thomas Lake. The shape of the channels appears to have been partly controlled by the subtle topography of the fluting/remnant ridge landforms.

South of the confluence of these subtle flutings/remnant ridges, a large trough originates from the relatively flat plain west of the hummocky terrain, and sweeps southeast to eastward through the Sedgewick area (Figure 2.5). This trough is narrow and well-defined in the north, widening as it arcs toward the east. The eastern-northern margin of the trough is abrupt against the higher hummocky terrain, whereas the southern margin gradually merges with the surrounding terrain, maintaining a less-curved path. Contained within this trough are parallel, curvilinear, flutings/remnant ridges (Figures 2.5 and 2.6a). The topographic expression of these flutings/remnant ridges is variable; many flutings are little more than long, shallow depressions, but features northeast of Sedgewick are well-defined and have trough to crest relief greater than 4 metres (Figure 2.6b). The remnant ridges usually have a higher leading end and gently taper to the southeast. The fan-shaped trough that contains these flutings/remnant ridges has been partly dissected by glaciofluvial channels and Iron Creek (Figure 2.6a). The truncation of this field by channels has eradicated the linear landforms in many places but the interchannel remnants are fluted, indicating that the entire surface was once a continuous field of flutings/remnant ridges. Remnant ridges have blunt stoss ends, with indistinct crescentic scours in places, though evidence for scours is usually absent. These remnant ridges are composed of diamicton with a clayey-silt matrix and numerous sand and gravel inclusions (Figure 2.6c). The diamictons are highly deformed with numerous examples of overturned folds and near-vertical alignment of gravel and sand stringers.

Gravenor and Ellwood (1957) mapped extensive glaciofluvial landforms in the Sedgewick area. Depositional, glaciofluvial landforms include kames and eskers and often these forms are closely associated with crevasse fills. All glaciofluvial depositional landforms either superimpose or truncate the fluted terrain. An esker, located in the largest fluting/remnant ridge tract, is roughly perpendicular to the remnant ridge landforms and is relatively continuous in the southern portion,

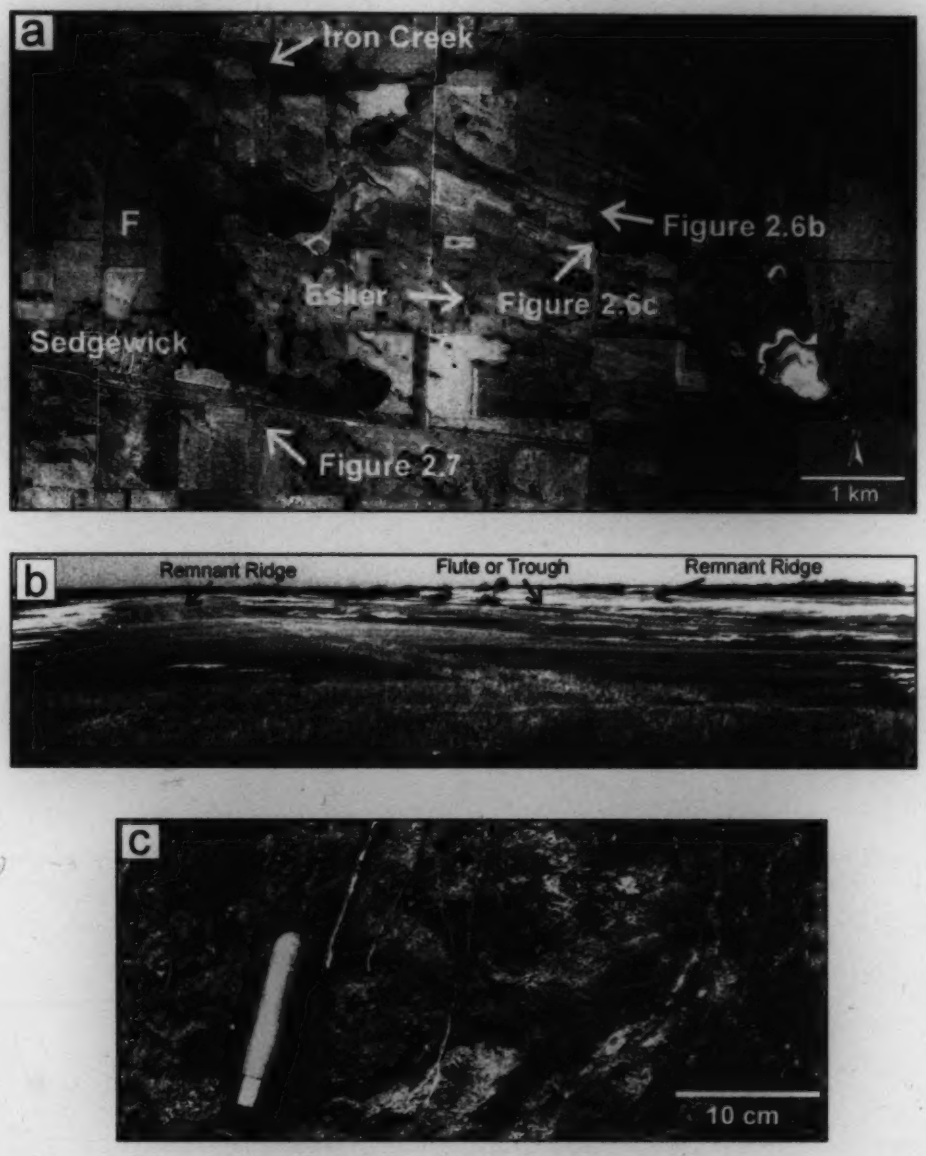

Figure 2.6: (a) Aerial photograph of the Sedgewick area illustrating the flutings/remnant ridges and the glaciofluvial landforms that truncate and superimpose them. The esker is continuous with a narrow meltwater channel to the north. (b) The remnant ridges have undulatory crestlines and are well-developed. (c) Sediments in the remnant ridges are highly deformed with numerous attenuated sand stringers and isolated pods of gravel and sand.

but disappears northward (Figure 2.6a). Where the esker disappears, two channels approximately the same size as the esker, truncate the remnant ridges. The southern end of the esker terminates at a fan. Another glaciofluvial landform in the Sedgewick area forms a curvilinear ridge, also oriented roughly perpendicular to the trend of the remnant ridges. This ridge is composed of well- to poorly-sorted gravel and sand that contains intraclasts of finer-grained material (Figure 2.7). This ridge is highly faulted, particularly along the lateral margins. These faults are normal and displacement is seldom greater than a few centimetres along any individual fault plane. Faults radiate from the centre of the feature indicating removal of lateral support after deposition.

Coronation-Spondin scabland

The Coronation-Spondin scabland (Sjogren 1993) is situated in the middle of the Torlea Flats, and occupies a broad, bedrock-controlled upland that projects northeastward (Figure 2.3b). This upland is characterized by several regional-scale ridge/trough landforms indicated in Figures 2.3, 2.4 and 2.8. Anabranching channels of the scabland are generally oriented toward the southeast, having been eroded into the regional-scale landforms. Erosion of the scabland has nearly obliterated the linear landforms, although the location of channels strongly reflects the former ridge/trough topography (Figure 2.8). The troughs originate at the relatively steep Castor Escarpment, south of the Battle River (Figure 2.8). These troughs are occupied by the largest channels of the Coronation-Spondin scabland, and any smaller, superimposed features, that may have been present on the ridge/troughs, have been obliterated by the scabland channels. The location and character of many smaller landforms in this area are related to the relief of these regional-scale ridge/trough landforms.

Beyond the limits of the incision of the scabland, and east of Coronation, numerous smaller suites of landforms are oriented both parallel and transverse to the regional-scale ridge landforms that characterize much of the Torlea Flats. Two different landform settings are important; first, north (lower elevation) of the Castor Escarpment, and second, south of the escarpment, on the upland. North of the escarpment, several examples of linear landforms are oriented parallel to the direction of the regional-scale ridges (Figure 2.8). These generally subtle landforms do not occur in fields, but rather as isolated, secondary forms within the regional-scale trough. One well-developed ridge and several subtle forms are aligned so that they coincide with a reentrant in the Castor Escarpment. The alignment of these linear landforms is maintained south of the escarpment, though locally there are significant departures from this trend.

South of the Castor Escarpment, discontinuous fields of parallel ridges rise above a gently

Figure 2.7: Highly faulted glaciofluvial sediments that overly the fluted terrain in the Sedgewick area. Sediments range from laminated fine sands and silts to plane-bedded gravel. Most of the exposure is composed of plane-bedded sands with some cross-bedding present. The faults are normal with minor displacement along any individual fault trace. Faults generally trend toward the margins of the feature, indicating removal of lateral support (presumably glacial ice) resulted in collapse.

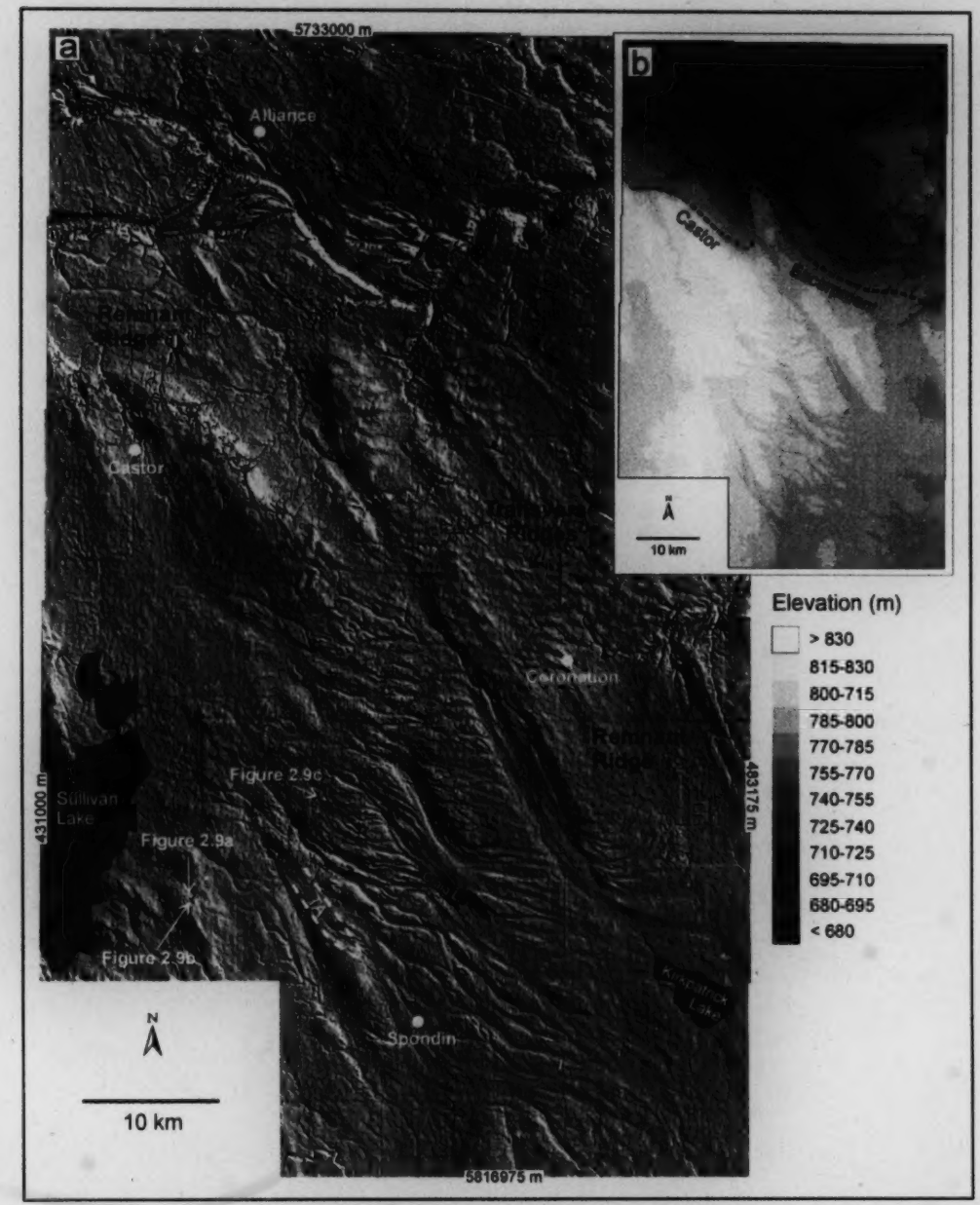

Figure 2.8: Topography of the Coronation-Castor area. (a) Hillshaded relief map, solar azimuth=60°, angle=40°. The regional-scale ridges are superimposed by transverse ridges and parallel, remnant ridges.The Coronation-Spondin scabland represents channelization and eastward diversion of flood waters. TA is an eroded anticlinal fold (glaciotectonic). (b) Classed elevation map illustrating the topographic setting and location of the Castor Escarpment.

undulating plain. Two well-defined ridges, east of Coronation, are straight and parallel, with their leading ends offset. The larger ridge has a paired crestline and a prominent leading end, but postglacial fluvial incision has destroyed any evidence there might have been for a crescentic scour. Northwest of these well-defined ridges is an east-west transition from transverse to parallel elements (compared to the regional-scale ridges/troughs). Transverse elements are relatively broad, low-relief landforms located within the trough north of Kirkpatrick Lake and are best developed on the northeast-facing slope of the regional-scale ridge. Further west, smaller parallel landforms are superimposed on the transverse elements. These small, relatively short ridges occur in groups and are best developed at the crest of the regional-scale ridge. The apparent transition from transverse to parallel forms occurs in conjunction with an increase in elevation toward the west. Small, parallel features, present on large-scale ridges further west, also show a preference for locally higher ground.

Southeast of Sullivan Lake, broad, elongate hills trend roughly northwest-southeast and are superimposed by smaller, slightly oblique, linear elements. These broad hills are steeper on the northwest ends and merge subtly with the terrain to the southeast. Smaller, parallel features between these large hills provide secondary undulations in the landscape (Figure 2.9a). These elongate hills are composed of Cretaceous bedrock, mantled only by thin soil (Figure 2.9b). The bedrock is largely undisturbed; minor folding in the bedding is present near the crests of the landforms. Southward, these broad hills are succeeded by hummocky terrain occupying higher ground around Sullivan Lake. To the east, within the Coronation-Spondin scabland, there are several streamlined hills found in isolation or in groups (Figure 2.8). These hills are typically composed of highly deformed diamicton with attenuated sand stringers (Figure 2.9c), resting directly on bedrock and bounded by areas devoid of glaciogenic sediment. One example of glaciotectonized bedrock in the western part of the area has been eroded by meltwater that formed the scabland (*cf.*, Sjogren and Rains 1995, their Fig.9a). The axis of this eroded, plunging fold is oriented roughly parallel to the broad hills that are composed of *in situ* bedrock, east of Sullivan Lake, and also to the distant Neutral Hills (Figures 2.3 and 2.8). These features, composed of glaciogenic sediment and bedrock, indicate that glaciogenic sediment was more pervasive on the Torlea Flats and widespread erosion has left the streamlined hills as prominent residuals.

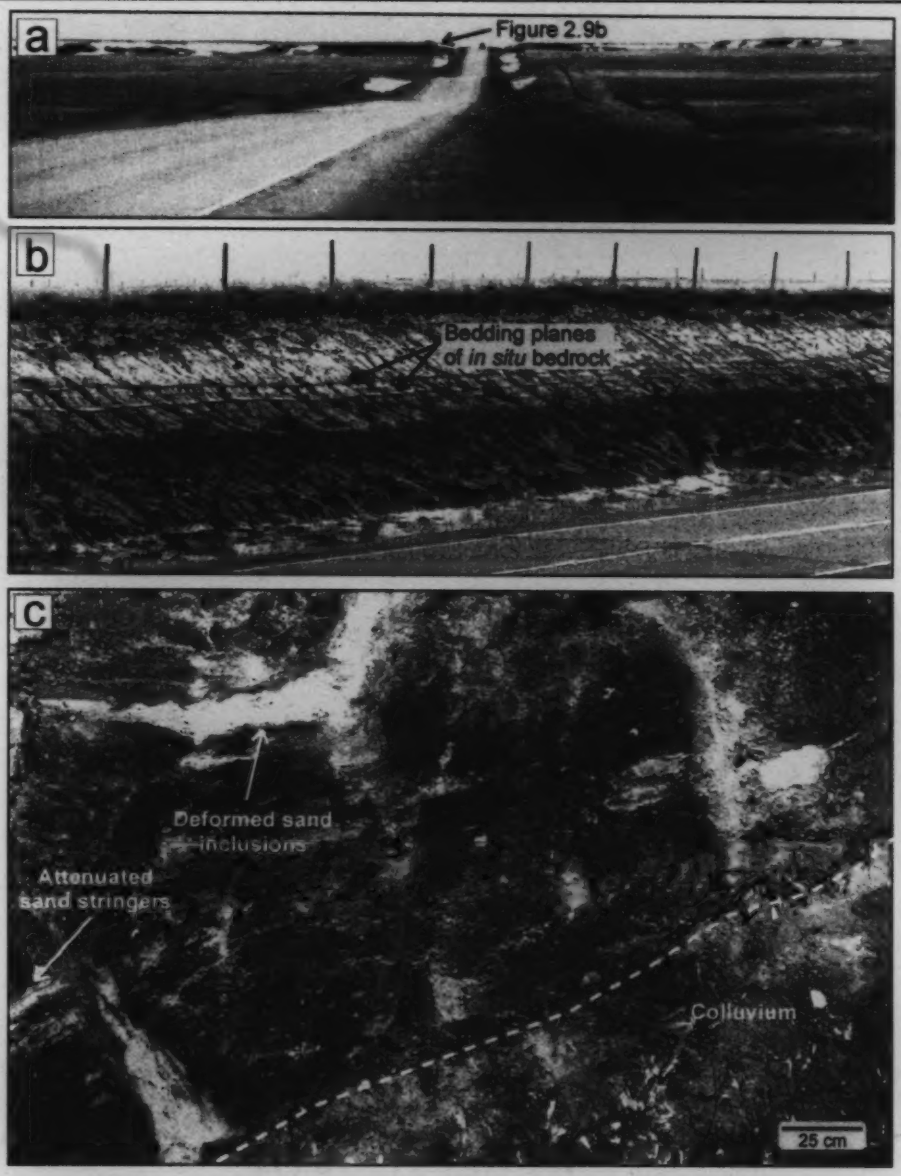

Figure 2.9: (a) Elongate, erosional landforms located southeast of Sullivan Lake. These features are composed of bedrock with only isolated occurrences of glacial material. (b) Upper Cretaceous bedrock in one of the larger features. The bedrock appears to be *in situ* but in some locations some minor folding is present. (c) Highly deformed diamicton with sand stringers in a streamlined residual. The combination of attenuated and injected sand bodies indicates that saturated sediment and high pressures were important during deformation of the sediment.

Discussion

The Torlea Flats and Multiple Glaciations

The paucity of glacial deposits, overlying saline Upper Cretaceous bedrock, in the Torlea Flats has resulted in the postglacial development of solonetzic soils over much of its length (*cf.*, Odynsky 1962; Rains et al. 1993). Warren (1937) suggested that the lack of glacial sediment was due to widespread erosion before glacial time and that the Torlea Flats are much older than features further east. The sequence of morainal systems in central Alberta has been the subject of many mapping studies, conducted by the Alberta Research Council. A recurring conclusion was that little, if any, evidence for multiple glaciations existed in the Torlea Flats (Gravenor and Bayrock 1955; Gravenor 1956), though multiple tills have been interpreted east of the Viking Moraine (Bayrock 1955) and in the Dinosaur Provincial Park area (Evans and Campbell 1992, 1995). The difficulty in explaining the existence of the Torlea Flats, in the context of multiple glaciations, led Gravenor and Bayrock (1955) to speculate that glacial erosion had removed preexisting Quaternary sediment and enhanced sliding prevented further deposition. The difficulty of explaining removal of sediment from *previous* glaciations is overcome if a single Laurentide glaciation affected the region (Young et al. 1994), although this does not adequately explain the existence of the flats.

Regional-scale Oriented Landforms

The process that removed glacial sediment in the Torlea Flats, must also have been responsible for the regional-scale landforms. The continuity of landforms in the Torlea Flats indicates that the formative process also operated at a scale comparable to the "Flats". Any hypothesis that explains the formation of the oriented landforms and in so doing, formation of the Torlea Flats, must be consistent with the morphology and sedimentology of the landforms. Several possible explanations for the regional-scale oriented landforms, include:

1. The ridges and troughs may be remnants of the preglacial drainage network. The ridges then represent interfluves and the troughs the paleotributaries.
2. The troughs are a result of postglacial fluvial erosion.
3. The ridges/troughs may be remnants of topography formed by compressional stresses associated with orogenic processes.
4. The ridges are glaciotectonic, formed at the margin of the Laurentide ice sheet. Thus, the ridges must be composed of stacks of bedrock and glacial sediment.
5. Ridges represent ice-moulded landforms parallel to the local flow of the ice sheet, presumably beneath an ice stream.
6. The ridges/troughs may be erosional remnants of a subglacial outburst flood(s) that flowed in a sinuous path through Alberta.

Preglacial drainage in Alberta generally flowed toward the north and east in valleys with a dendritic to parallel pattern (*cf.*, Pawlowicz and Fenton 1995). Bedrock valleys (Pawlowicz and Fenton 1995), are roughly perpendicular to the long axis of the Torlea Flats and are located where the regional-scale ridges are absent (Figure 2.3). The regional-scale ridges and troughs are more pronounced south of northward-facing, subtle escarpments (Figures 2.3 and 2.4). The interfluves of the preglacial drainage systems are coincident with the best developed ridge/trough fields. Although this juxtaposition exists, it is highly improbable that preglacial tributary development was wholly responsible for the wide troughs. It is difficult to imagine how several parallel tributary valleys about 5 km wide and 20 m deep developed on an interfluve approximately 25 km wide. The catchment for these tributaries would have been very small and unlikely to contribute enough runoff to form broad, closely spaced valleys. However, the spacing of the regional-scale ridges is similar to adjacent creek systems which indicates that, even though preglacial fluvial action was likely not the only erosional agent, it probably did exert some influence on postglacial landscape development.

If the ridges/troughs are preglacial in age, the lack of glacial material must be addressed. Many of the ridges are partly composed of diamicton and the troughs often contain exposed bedrock. Preglacial valleys in the area are largely filled with fluvial sediment and glacial material (e.g., Evans and Campbell 1995). The apparent contradiction that glacial sediment is found both on high and low points makes it difficult to infer enhanced sliding and nondeposition associated with packing of basal ice with bentonitic clays (Gravenor and Bayrock 1955). Another problem with this explanation is that the Torlea Flats and oriented ridges are nearly perpendicular to the presumed direction of ice advance in the area. It is difficult to envisage why an ice sheet would be non-depositional in a narrow, sinuous zone transverse to flow direction while depositing large amounts in areas such as the Viking and Buffalo Lake "Moraines".

Another possible explanation for the regional-scale ridges/troughs relates to postglacial fluvial erosion (Warren 1937). Arguments against this idea are similar to those for the preglacial valley hypothesis. Postglacial fluvial systems in Alberta were characterized by rapid downcutting, where tributaries were out of phase with larger rivers that acted as local base levels (Rains and Welch 1988; Rains et al. 1994). Because of this rapid lowering of local base levels, fluvial systems in postglacial Alberta were primarily incising rather than cutting laterally. The contemporary river systems are deeply incised, whereas, the regional-scale ridges/troughs are broad and shallow. There are many incised channels on the ridges/troughs, but they do not form a well-developed drainage network and often do not conform to the erosion pattern defined by the regional-scale ridges/troughs.

If removal of glacial material from the Torlea Flats was by postglacial fluvial action, the massive amount of glacial material removed, in addition to the absence of deeply incised channels, requires flows much larger than presently observed.

Another possible hypothesis for formation of the ridges/troughs is that they were associated with orogenic processes. There is some evidence that compressive stresses, associated with a convergent plate boundary, could have influenced the location/orientation of some of the regional-scale ridges/troughs. Progression from overthrust faulting in the mountains to low amplitude folding in the plains would result in parallel lineations far from the mountain front. The eastward propagation of these stresses likely formed minor topographic undulations that were later accentuated by various erosional processes. This tendency for erosional processes to exploit preexisting structural weaknesses is referred to as tectonic predesign (Eyles et al. 1997). The nearly parallel orientation and similar spacing of creeks northwest of Drumheller, and the regional-scale ridges/troughs, indicates that low amplitude folds in the underlying Cretaceous and Tertiary bedrock may have been exploited by erosional processes (preglacial, glacial, and postglacial). Attempts have been made to correlate fractures in bedrock to fractures in surficial material (e.g., Rumsey 1971; Babcock 1977) and indications are that the surficial jointing patterns are not directly related to subsurface geology. If the pattern of creeks and regional-scale ridges is not related to subsurface processes then the parallelism is highly coincidental.

Glaciotectonic landforms are common in central Alberta (*cf.*, Kupsch 1962; Fenton and Andriashek 1983; Tsui et al. 1989) and it is conceivable that these regional-scale ridges and troughs owe their existence to glaciotectonic disturbances. Glaciotectonic landforms are usually expressed, topographically, as arcuate hills of stacked bedrock and diamicton slabs, often with a concave-up-glacier orientation and paired with a "hole" that represents the source area for the thrust material. These tectonic landforms are usually obvious in air photographs (Gravenor et al. 1960; Smith 1987) and appear as corrugations. The regional-scale ridge/trough landforms show none of the topographic characteristics typical of thrust terrain, and occur on a much larger scale than is usual for glaciotectonic terrain in the area. However, isolated examples of glaciotectonic folding are present, and one example is associated with a regional-scale ridge (Figure 2.8). This dipping anticline has been eroded but the fold is still discernible (Sjogren and Rains 1995, their Fig. 9a). The axis of this fold is roughly parallel to the orientation of the regional-scale ridges/troughs and is located on a northeast-dipping slope (Figure 2.3). Therefore, it is apparent that the process that formed the regional-scale ridges/troughs postdated the glaciotectonic emplacement of the folded Cretaceous

bedrock.

Many theories have been developed to explain the formation of drumlins and flutings, most of which involve the erosion or accretion of sediment by glacier ice (e.g., Boulton 1976, 1987; Shaw 1980; Boyce and Eyles 1991; Hart 1995), or subglacial water (e.g., Shaw and Kvill 1984; Shaw and Sharpe 1987; McCabe and Dardis 1989; Shaw et al. 1989; Shaw 1996). In some cases, ice streams, zones of fast flowing ice bounded on both sides by slower moving glacier ice, and usually terminating at an ice shelf (Paterson 1994), have been implicated in the formation of oriented landforms by erosion or accretion of subglacial sediments. Many different mechanisms have been invoked to explain these zones of fast flowing ice including enhanced deformation of basal ice, and sliding (Iken et al. 1993) and/or deformation of saturated basal till (Alley et al. 1986, 1987; Blankenship et al. 1989). In east-central Alberta, an extensive field of fluted terrain has been attributed to ice streams (Mougeot 1991; Wilson 1997). Wilson (1997) inferred an ice stream on the basis of the glacial deposits and fluted landforms and used low pre-consolidation values to infer high porewater pressures in basal tills.

The regional-scale ridges/troughs, described in this paper, are unlike drumlins or flutings as they have been described in the literature but are rather large, topographically subtle, parallel to subparallel features. These landforms could not have been formed by deformation of glacial sediment (e.g., Boulton 1987; Hart 1995) because they are composed primarily of bedrock with a cap of glacial diamicton. Because the ridges are mainly composed of bedrock, overlain by thin to discontinuous diamicton, formation by accretion (e.g., Paul and Evans 1974; Boulton 1976) is not plausible. Furthermore, the widespread presence of boulder lags is inconsistent with a deforming bed mechanism. Also, bedrock is often exposed in the troughs, therefore formation by a deforming bed (Boyce and Eyles 1991; Hart 1995) is precluded. If ice streams are initiated and maintained by deformation of low shear strength sediment, then there should be significant throughput of sediment transported to the ice margin. If an ice stream did pass through central Alberta then it must have followed a sinuous path (including the Torlea Flats) and deposited a significant volume of deformed sediment in a terminal moraine. The only morainal zone that could conceivably be associated with an ice stream is the Lethbridge moraine which is within the margins of maximum Late Wisconsinan Laurentide extension (Dyke and Prest 1987). The Torlea Flats and contiguous "scoured" terrains are, for the most part, devoid of glacial material that could be associated with such a deforming bed. For that reason, erosion of deforming beds, as presented by Boyce and Eyles (1991) and Hart (1995), is not compatible with the observations in this area.

Another argument against pervasive deformation and/or ice streams forming the oriented landforms and the Torlea Flats, is related to the topographic setting and expected glaciological dynamics. Much of the Torlea Flats is oriented north to south with sinuous sections that are generally oblique or parallel to the trend of the regional slope. In areas where the "Flats" are oriented up the regional slope, glacier flow would have been compressive and should have formed glaciotectonic landforms (*cf.*, Aber et al. 1989). There are many glaciotectonic landforms adjacent to the Torlea Flats that indicate thrusting from south to southeasterly flowing ice (for example Flagstaff Hill, Figure 2.3). However, most of the area has little glacial sediment and few glaciotectonic landforms, although there is some evidence of glaciotectonics perpendicular to the orientation of the Torlea Flats (Figure 1.3). Implicating an ice stream in the formation of the Torlea Flats and oriented landforms is problematic because flow up an escarpment such as the Castor Escarpment must have been compressive and not extensional as is typical for ice streams (Paterson 1994). Also, a body of water, large enough to create a drawdown effect by producing a marginal zone of zero basal shear stress, would not have been present. There must be a mechanism of removing ice from the terminus of an ice stream to maintain an ice stream for any length of time. Therefore, even though the continental-scale analyses of Marshall et al. (1996) indicated that this area was predisposed to ice streams, the regional topography and landform/sediment associations preclude formation by ice streams maintained by deforming beds.

Another hypothesis regarding the formation of oriented landforms involves erosion and/or deposition associated with catastrophic releases of stored subglacial meltwater. This idea was originally invoked to explain the morphologic similarities between drumlins and erosion marks formed by turbulent flows (Shaw 1983). The regional-scale ridge/trough fields are dissimilar landforms from those generally described by Shaw and colleagues because they do not possess crescentic scours on the presumed proximal ends and they are much larger than any drumlins or flutings associated with these hypothetical floods. The scale of these landforms is similar to "subparallel scour zones or bedrock megachannels" thought to be associated with initial stages of channelization of a hypothetical, subglacial sheet flood (Brennand and Shaw 1994). Brennand and Shaw (1994) showed broad subparallel scours up to 8 km wide and 27 km long, very similar to the size of the regional-scale ridges/troughs described in this paper. They suggested that bedrock megachannels were, at least, modified by a collapsing water sheet during the first phase of channelization and that scouring may have been partially accomplished by preglacial tributaries and glacier ice.

Diversions/Deflections

The outlines of the Torlea Flats and the flanking morainal systems, are not smooth and well-defined. Rather there are numerous topographically distinct diversions, constrictions and expansions of the Torlea Flats. Many of these perturbations are associated with fluting/remnant ridge fields and other landforms. One significant diversion from the "Flats" is the trough, arcing though the Sedgewick district. In this setting it is important to reiterate that the trough is continuous with the Torlea Flats. Diversions pose a difficult problem when attempting to invoke ice streams and/or deforming beds for explaining the landform/sediment assemblage. If an ice stream was implicated in the formation of this trough, the faster moving ice (in the Torlea Flats) would have intruded into the confining ice at an angle approaching 90°, while eroding the substrate. It is difficult to explain how ice moving differentially could divert into the more sluggish, confining ice. Also, if bed deformation was the cause of this diversion, sediment transported through the area would have been deposited where the ice stream ended; a sediment accumulation like this does not exist. In addition, ice flowing down the Torlea Flats would have had to climb the approximately 100 m high Castor Escarpment and then divert toward the east. It seems highly improbable that streaming ice could first undergo several diversions, expansions, and constrictions while maintaining extending flow up the regional slope, without an obvious drawdown mechanism.

Interpretation

The inadequate explanation of the Torlea Flats, regional-scale ridges/troughs and the diversions/deflections of landforms in the area by a purely glacial erosion mechanism is apparent. Therefore, we must consider another mechanism(s) that more satisfactorily explains the landform/sediment associations. The subglacial sheetflood hypothesis meets with considerable opposition in the scientific community. However, its ability to explain individual landforms, sediments, and associations of different landforms has made it attractive. The Torlea Flats have been an enigmatic component of the central-Alberta landscape, but if removal of glacial sediment was caused by catastrophic releases of subglacial meltwater, the Torlea Flats and adjoining landform suites comprise an integrated system. Rains et al. (1993) and Shaw et al. (1996) have invoked at least one large outburst of subglacial meltwater (the so-called Livingstone Lake event) to explain erosion of several anabranching pathways in Alberta. Though this outburst flood hypothesis is efficient in explaining the anabranching character of scoured terrain in Alberta many details about the erosive and depositional effects of this deluge were dependent on local conditions.

The eastern flow path (Figure 2.2) of Rains et al. (1993) and Shaw et al. (1996) is a topographically distinct feature, formed by a subglacial sheetflood that progressively channelized to form many of the local features. The sheetflood inundated the landscape, occupying areas that minimized the resistance to flow, even though the water was being forced tangentially up the regional slope toward the ice sheet margin. The sheet temporarily submerged topographically high points only slightly modifying the preexisting subglacial topography. The inherent instability of sheetflow (Walder 1982, 1996), compounded by the dramatic topographic control on the lateral pressure gradients, caused the sheet to eventually break down into large anabranching paths. Zones of locally high hummocky terrain, no longer modified by the flood water, were initial recoupling-areas that caused flows to be rerouted. The down-flow translation of glacier ice during this recoupling explains the presence of some glaciotectonic landforms along the flood paths (e.g., Flagstaff Hill). As the hydraulic head decreased, the highest outlets for this subglacial flood were abandoned and the progressively channelizing flow was diverted through lower outlets. As higher outlets were abandoned so, too, were the highest paths of the anabranching network. When this happened, a larger portion of the rapidly decreasing discharge was diverted through the eastern flow path (Torlea Flats). The northward progression of abandonment resulted in cross-cutting landform suites, one example being the Coronation-Spondin scabland truncation of the Sheerness fluting/remnant ridge field (Rains et al. 1993; Sjogren 1993; Sjogren and Rains 1995; Shaw et al. 1996). Accompanying the diversion was the tendency toward development of channel forms such as the scabland (Sjogren and Rains 1995).

Based on the similar orientation and spacing of bedrock structure patterns to the west, and glaciotectonic features in the area, the regional-scale ridges/troughs are most likely polygenetic. First, the influence of compressional stresses associated with orogenic processes created a generally northwest-southeast trend to the preglacial, lower order, drainage basins in the area. The stress field provided the "predesign" for regional-scale landforms (Eyles et al. 1997). These subtle topographic irregularities resulted in differential erosion preglacially, glacially, and postglacially. The northeast slope to the land resulted in an ideal setting for glaciotectonics as the Laurentide ice sheet moved upslope across the plains. The subglacial sediment tended to mask the preexisting topographic irregularities. As the subglacial sheet flood(s) commenced, the irregularities in the subglacial landscape lead to zones where the water was deeper and hence concentrated the erosion. The rerouting and progressive channelization of the sheetflood(s) resulted in many areas being left "high and dry", only slightly modified by the flood erosion. Thus, the locations of the flood paths were

controlled by the existing topography that was largely dictated by the bedrock topography and the location of preglacial valleys and interfluves. The discontinuity of the regional-scale ridges in the Beaverhill Lake area is the result of the floodwaters not entirely conforming to the topography but creating ridges and troughs where the high points in the preglacial drainage divides were crossed. The location of thick glacial sediments is primarily a result of the location of the preglacial depressions related to the major ancestral river systems.

The diversions in the study area, shown in the Viking-Sedgewick and the Coronation-Spondin districts, indicate rerouting of the subglacial sheet flood as the discharge rapidly dropped. In the south, the bedrock residuals east of Sullivan Lake are oriented at an angle that is consistent with water being routed through the Sullivan lake basin and around the much higher hummocky terrain to the south (part of the Buffalo Lake moraine). The truncation of the glaciotectonics indicated by Sjogren and Rains (1995), and formation of the Coronation-Spondin scabland, would have quickly followed the diversion of meltwater that streamlined the bedrock residuals east of Sullivan Lake. The transverse ridges and remnant ridges along the Castor escarpment are the result of obstacles emerging into the floodwaters. Many of these remnant ridges are likely topographic irregularities inherited from the preglacial landscape.

In the Viking area the convergent remnant ridges are the result of the primary flow in the eastern flow path encountering flow from the Birch Lake depression. Flow convergence resulted in a highly erosive zone that formed the arcing trough through the Sedgewick area. Flutings/remnant ridges in the Sedgewick area indicate that the arcing trough was an extension of flow that inscribed the Torlea Flats. The superimposition of glaciofluvial landforms, roughly at right-angles to the remnant ridges, indicates that the postflood glacier hydrologic system had radically reorganized itself. The reason that the diversion occurred in the Sedgewick area is explained by the configuration of the preglacial topography. It is unlikely that glacial erosion/deposition completely removed the topographic expression of the ancestral Red Deer River valley, therefore, this area was probably a saddle in the subglacial topography. As the flood discharge dropped, diversion took the path of least resistance. This linkage is important because the preglacial topography was only mantled by glacial sediments and these topographic irregularities would have been the major control on the location of rerouted subglacial meltwater.

Conclusions

The subglacial flood hypothesis has been the subject of considerable skepticism in the scientific community (Benn and Evans 1998) even though an increasing body of geomorphic evidence substantiates the idea. This paper illustrates that evidence for subglacial floods in central Alberta not only relates to the types of landforms but also to the continuity of landforms throughout the floodpaths, and particularly to flow diversions. The location and topographic expression of landforms associated with subglacial releases of meltwater of this magnitude were partly controlled by preglacial topography and drainage networks that were inherited from the underlying bedrock.

Glaciation in Alberta did little more than mantle the preglacial topography with sediment and, locally, redistribute some of the Cretaceous bedrock. At least one outburst of subglacial meltwater inundated much of the subglacial landscape, initially as a sheetflow and subsequently as broad, partly channelized flow. The locations of anabranching patterns of meltwater erosion through Alberta were partly controlled by the local topographic configuration. Erosion was accentuated where deeper water flowed. Erosion of the substrate, coupled with decreasing discharge, further channelized the flow and as the pressure head decreased higher outlets were abandoned and a larger proportion of the meltwater was rerouted down the regional slope.

The distribution of glacial sediment, and the integrated relationships between the regional-scale ridges/troughs and landforms in the diversion zones, preclude formation by ice streams, either by subglacial deformation or sliding. It is also clear that pre- and postglacial fluvial erosion only played a secondary role to subglacial meltwater erosion in the development of the landscape morphology in central Alberta.

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Chapter Three: Laurentide Meltwater Channels and Formation of the Viking Moraine, east-central Alberta.

Introduction

Problem Statement

Ice-marginal landforms are commonly the only available evidence for reconstructing the paleogeography of the retreating Late Wisconsinan Laurentide ice sheet in western Canada. Inconsistencies in these reconstructions arise because of the difficulty in differentiating between preglacial, subglacial, ice-marginal, and proglacial landforms. To compound this problem, some landforms may relate to earlier glacial episodes (Klassen 1989).

Morainal landforms are commonly interpreted with the presumption that hummocky terrain, which comprises much of the moraines, forms as supraglacial debris is released from stagnating glacier ice (Gravenor and Kupsch 1959), even though other hypotheses on the formation of hummocky landforms exist (*cf.*, Hoppe 1952; Stalker 1960; Shaw and Ashley 1988; Holden 1993; Rains et al. 1993; Munro and Shaw 1997). Glaciofluvial channels associated with hummocky terrain are either assumed to have formed prior to the hummocky terrain (i.e., predating the advance that deposited the till), in ice-walled stream trenches (Gravenor and Bayrock 1956; Parizek 1969), as glacial spillways (Kehew 1982) or as subglacial channels (Evans and Campbell 1995). It is often difficult to differentiate between various paleoenvironments and occasionally necessary to invoke multiple glacial advances to explain the landforms and stratigraphic associations.

Glaciofluvial channels, associated with the Viking Moraine in east-central Alberta, possess a wide variety of morphologic and sedimentologic characteristics which indicate that a simple model of ice-marginal formation is inadequate. To explain the formation of the Viking Moraine it is necessary first to understand the genesis and timing of meltwater channels that dissect it.

Erosional Glaciofluvial Channels

Glaciofluvial landforms have received significant attention in the scientific literature because they represent the systems responsible for transporting the vast quantities of meltwater away from glaciers. The geomorphology and sedimentology of these landforms can provide information about the hydrologic systems of glacial paleoenvironments. Generally, there are two settings for the formation of glacial meltwater channels; subglacial and subaerial. Laurentide subaerial channels

drained water away from the glacier terminus or from proglacial lakes. The flow regimes of these channels were controlled by the diurnal and seasonal fluctuations in meltwater production and the release of supraglacial and subglacial stored water. Probably the most-studied subaerial channels are those associated with catastrophic draining of proglacial lakes (e.g., Bretz 1969; Baker and Nummedal 1978; Clayton 1983; Teller and Thorleifson 1983; Kehew and Lord 1986; Evans 1991; Kehew 1993; Smith and Fisher 1993; Fisher and Smith 1994). Interpretations on the sequence of channel usage are critical for reconstructing the configuration of the Laurentide ice sheet during deglaciation. Meltwater channels on the Canadian prairies are often assumed to represent a subaerial environment, which has led to complicated reconstructions of ice margins (*cf.*, Bretz 1943).

Spillways are usually single channels with occasional anabranching reaches. These channel assemblages are discontinuous, starting at an upper glacial lake basin and often terminating at large deltas in a lower lake basin (Smith 1994). Drainage of proglacial lakes was often initiated either by hydrostatic lifting of an ice dam, or by breaching of an earthen dam (Kehew and Lord 1987). Once initiated, drainage occurred catastrophically, causing drainage of the receiving basins in a domino-like progression (Kehew and Clayton 1983). The locations and morphologies of these channel networks were controlled by topography, geology, ice sheet margins, preexisting channels, and isostatic depression (e.g., Baker 1978a; Kehew 1982; Kehew and Clayton 1983; Teller and Thorleifson 1983). Generally, time-transgressive sequences of spillway channels, on the Canadian prairies, can be identified as reflecting the ice sheet retreat down the regional slope (Bretz 1943; Kehew and Lord 1986).

Catastrophic releases of meltwater created channels with predictable morphologies. Kehew and Lord (1986) presented a developmental sequence in the formation of spillways (Figure 3.1a). This sequence follows very closely from the work of Shepherd and Schumm (1974) and demonstrates the tendency for shallow flows or sheet flows to channelize. Many geomorphic characteristics such as streamlined erosional residuals, longitudinal grooves, and boulder lags, were illustrated by Kehew and Lord (1986, 1987), and have also been documented in the Channeled Scabland of Washington State where multiple, catastrophic outbursts from Glacial Lake Missoula inundated the Columbia Plateau (Baker 1978b). Bryan et al. (1987) and Evans (1991) implicated the progressive channelization of broad sheetflows in the development of part of the Red Deer River valley, Alberta.

Subglacial counterparts of spillway channels are tunnel valleys. Tunnel valleys are large,

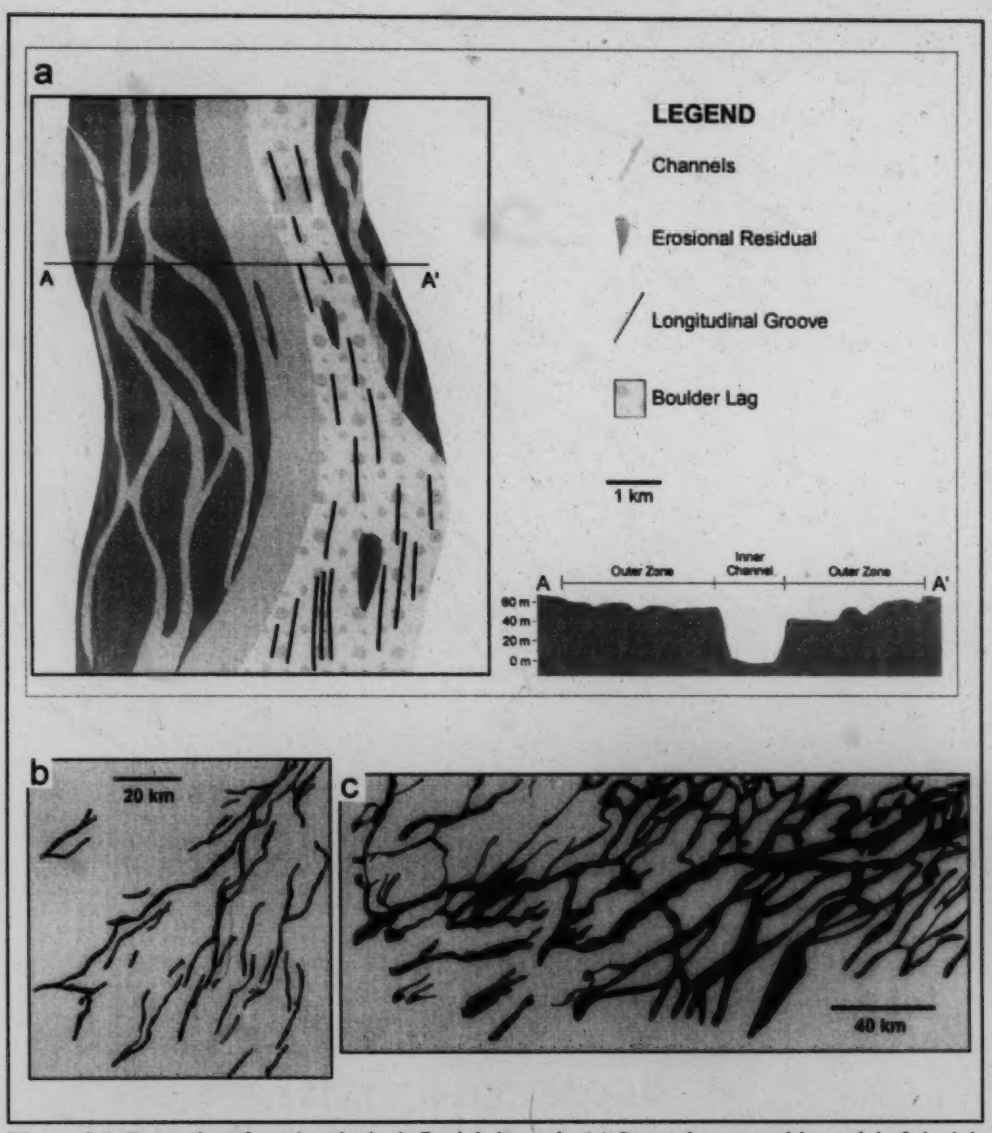

Figure 3.1: Examples of erosional, glaciofluvial channels. (a) General geomorphic model of glacial-lake spillway morphology (modified from Kehew and Lord 1986). First, inundation causes the flow to be conveyed in shallow, anabranching channels with irregular-shaped residuals. Second, further erosion streamlines the residuals and an inner channel is initiated. Third, longitudinal grooves form on the upper surface adjacent to a well-developed inner channel. Fourth, the flow is conveyed in the inner channel. (b) Distribution of tunnel valleys in part of Minnesota (modified from Patterson 1994). Note the relatively straight channels that radiate in a fan-like pattern. (c) Anabranching tunnel channels in southern Ontario (modified from Shaw and Gilbert 1990). Note that there are many discontinuities in the channel pattern and the sizes of individual channels are highly variable.

elongate depressions cut into bedrock or glaciogenic sediment (Grube 1983). Tunnel valleys may form integrated anabranching patterns, relatively straight discontinuous segments, or radial patterns (Figure 3.1b). They often have asymmetric cross-sections and may be up to 400 m deep, 4 km wide, and greater than 100 km long (O' Cofaigh 1996), although their dimensions are highly variable. One common observation is that gradients of tunnel valleys do not always conform to the regional slope and the channels often have uphill, undulatory, and/or convex-up longitudinal profiles (e.g., Boyd et al. 1988; Shaw and Gilbert 1990; Wingfield 1990; Booth and Hallet 1993; Sjogren and Shaw 1996). Also, tunnel valleys may contain subglacial landforms such as drumlins and eskers (Booth and Hallet 1993; Brennand and Shaw 1994). Sedimentary infills of tunnel valleys may include glacial till (Piotrowski 1994), but are more commonly composed of sediment gravity flow material, glaciofluvial gravels and sands, and fine-grained suspension deposits (O' Cofaigh 1996). Commonly, tunnel valleys contain thick sequences of well-sorted sands and gravels that may have proximal to distal fining trends (Ehlers and Linke 1989; Sjogren and Shaw 1996). The sediment in some tunnel valleys is largely contained within transverse bedforms such as gravel dunes (Shaw and Gorrell 1991; Brennand and Shaw 1994), that indicate sedimentation from catastrophic meltwater flows. Some tunnel valleys terminate at large gravel fans, up to 80 m thick, that may represent ice marginal positions (Patterson 1994).

Several theories have been developed to explain the formation of tunnel valleys. Undulatory longitudinal profiles and nonconformity with the regional slope require that tunnel valleys formed subglacially, under pressure (Mooers 1989; Booth and Hallet 1993). The two main controversies surrounding tunnel valley formation are: (1) were the formative flows steady state or catastrophic, and (2) did they form as integrated systems or segmentally? Boulton and Hindmarsh (1987) presented a steady state model of tunnel valley formation where subglacial sediments with low transmissivities deform into R-channels and are removed. Continuation of this process would allow formation of a large tunnel valley from a relatively small conduit. A second group of theories involves incremental formation of tunnel valleys along a retreating glacier front. Wingfield (1990) envisaged formation of the valleys by a headward-eroding plunge pool, whereas Mooers (1989) implicated supraglacial meltwater, draining to the retreating glacier's bed, for the erosion. Patterson (1994) also advocated a time-transgressive formation for tunnel valleys based on the presence of fans. A third group of theories implicates catastrophic releases of meltwater and integrated tunnel valley networks (Wright 1973; Boyd et al. 1988; Ehlers and Linke 1989; Shaw et al. 1989; Shaw and

Gilbert 1990; Brennand and Shaw 1994; Piotrowski 1994). A catastrophic origin is inferred largely on the basis of the integrated anabranching pattern, undulating thalwegs, scour pools and landform associations with flutings, drumlins, eskers, and bedrock erosion marks (O' Cofaigh 1996).

A distinction should be made between "tunnel channels" and "tunnel valleys". The traditional term "tunnel valley" has been replaced by some authors with "tunnel channel" because the latter is appropriate when the feature is inferred to have been largely full during much of its formation (e.g., Brennand and Shaw 1994).

Study Area

The study area is located in east-central Alberta on a portion of the Viking Moraine (Figure 3.2). The hummocky terrain that dominates this morainal system extends NNW-SSE in this area and is cross-cut by several sets of meltwater channels and some areas that are largely devoid of Quaternary sediments (Sjogren and Rains 1996). Meltwater channels that dissect the Viking Moraine are found in zones with thick Quaternary sediments as well as those lacking such material. Although glaciofluvial channels are present throughout the area they have very different morphologic and sedimentologic characteristics from place to place.

Moraine plateaux, eskers, flutings/remnant ridges, glaciolacustrine basins, crevasse fillings and glaciotectonized terrain are interspersed with the hummocky terrain, producing discontinuous zones of hummocky terrain within the morainal system. Extensive systems of glaciotectonic ridges, the Neutral Hills, are located along the southern part of the study area. These hills are composed of imbricate slabs of Cretaceous bedrock and are often mantled with glaciogenic sediment. Northward, glaciolacustrine sediments interfinger with hummocky terrain and glaciofluvial sediments. These sediments are most prominent in the area east of the Battle River, south of the town of Wainwright, with less extensive sedimentary bodies farther west and north. The Viking Moraine is separated from a large area, more or less devoid of Quaternary sediments, by a relatively sharp, bulbous contact zone. The boundary between of high-relief hummocky terrain of the Viking Moraine and the undulatory terrain to the west defines several reentrants where Upper Cretaceous bedrock is exposed at the surface. Landforms within these reentrants indicate widespread removal of Quaternary sediments.

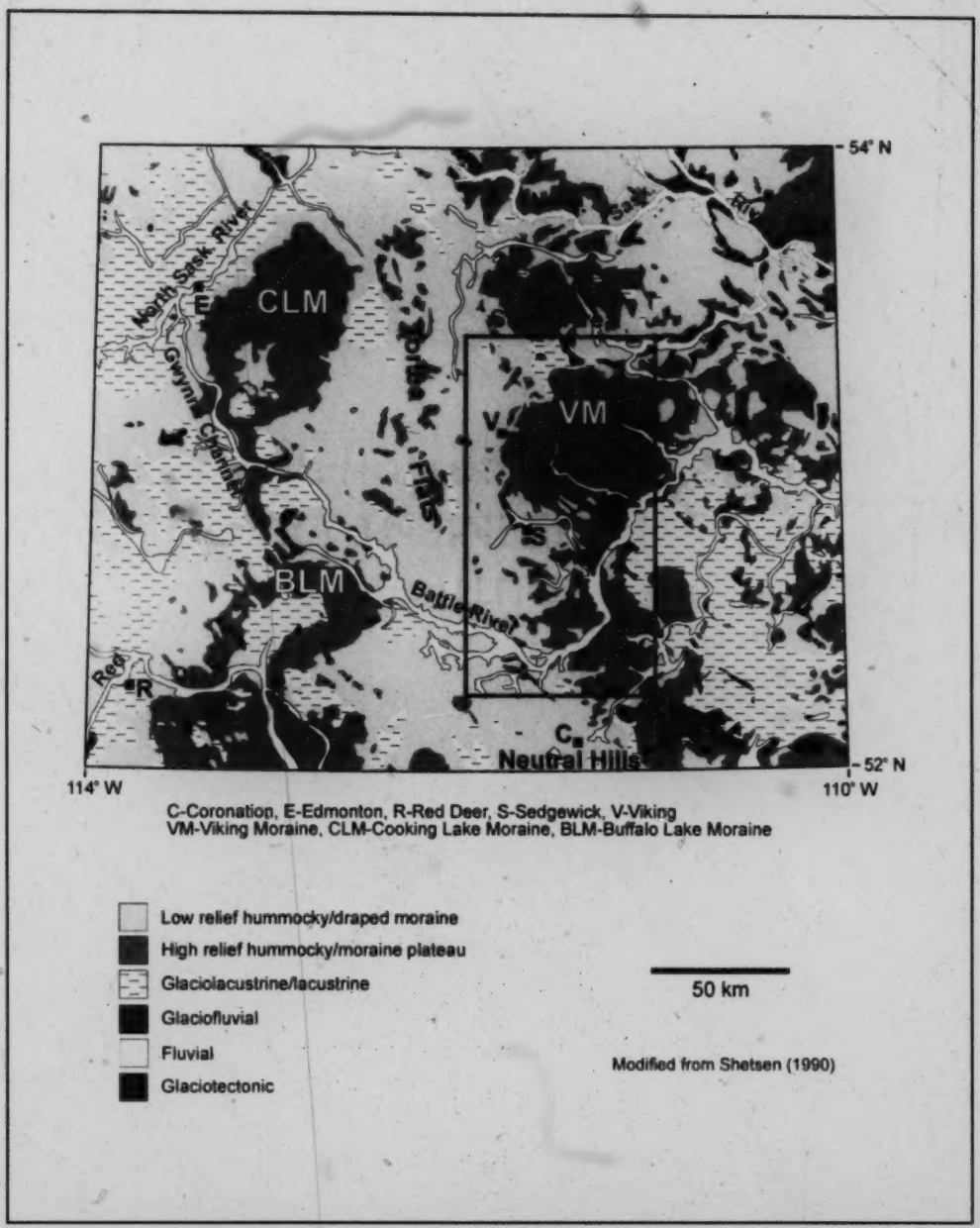

Figure 3.2: Location of the study area in east-central Alberta. Surficial deposits and landforms have been generalized from Shetsen (1990). The study area is located in a large bulbous portion of the Viking Moraine, separated from the Cooking Lake and Buffalo Lake moraines by the Torlea Flats. The boundary of this system of hummocky terrain is sinuous, dissected by several systems of glaciofluvial channels, glaciotectonized terrain, exposed bedrock, and lacustrine plains.

Terrain Modelling

There are three sources of digital data used in this paper. First, raster digital elevation model (DEM) data at a scale of 1:20,000. were obtained from the Alberta Government These data were produced with commercial software (SCOP) using direct measurements from aerial photographs. These 1:20,000 DEMs were sampled at 25 m intervals. The minimum allowable vertical accuracy of photogrammetrically captured points is such that 90% have errors less than 3 m, relative to the stereo model datum; 90% of interpolated points have errors less than 5 m (Land Information Services Division 1988). DEMs are georeferenced using NAD27 and displayed in a UTM projection (Grid Zone 12U).

Qualitatively, errors in the data take on a number of forms. The most evident errors are at the junction of two orthophoto sets, as orthogonal edges, where the entire adjacent data set is vertically displaced. These errors arise from a discrepancy between stereo model datums used during initial data capture. Other errors, evident in low relief areas, are regular patterns of north-south oriented ribs in the hillshade model. Other artifacts of the initial data capture are regularly spaced pits or bumps.

Digital Terrain Elevation Data (DTED), obtained from the Products and Services Division, Natural Resources Canada, Ottawa, were used for displaying the regional topography. These data were acquired from secondary sources and have 3 arc-second spacing in latitude, 6 arc-second spacing in longitude, and vertical accuracies of ±30 m. The third type of data were obtained from the Alberta Research Council as digitized bedrock topography contours. These contours were interpolated from boreholes and the final DEM was created by surfacing the digitized points using a multiquadric technique (Hemenway 1995). Both the DTED data and bedrock DEM are displayed at approximately 210 m resolution.

The Characteristics of Glaciofluvial Channels

Glaciofluvial channels (except the Battle spillway/Gwynne outlet, Figure 3.2) in the study area generally range from 0.3-1.0 km in width, though individual channels do reach 2.3 km wide. Uninterrupted channel segments are highly variable in length, ranging from a few hundred metres to in excess of 50 km in the case of Grattan Creek (Figure 3.3). Channel segments range from a few metres to over 35 m in depth and can change dramatically along their length. Channel depth is closely related to the morphology of the channel in plan view and to the character of sediment into

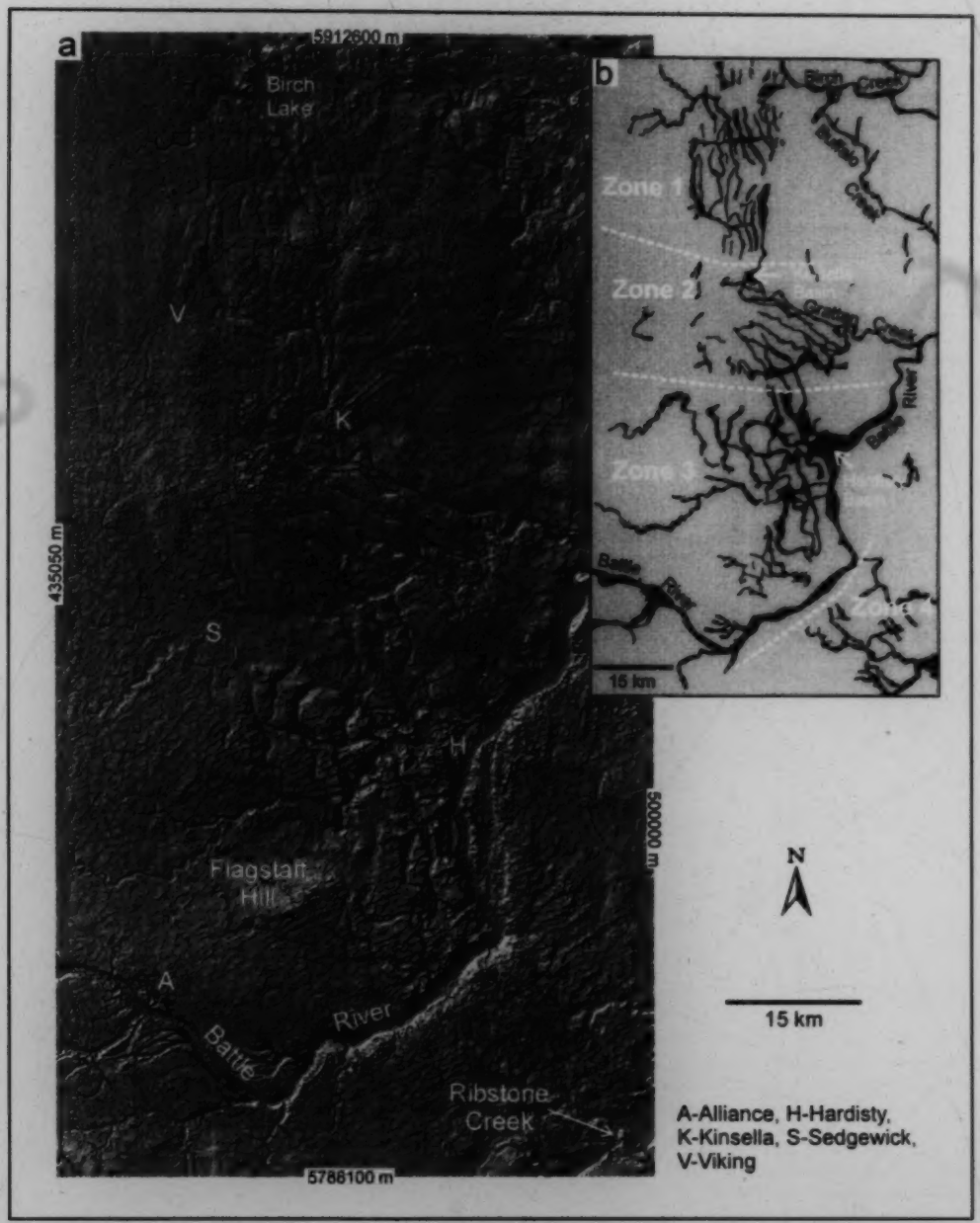

Figure 3.3: Study area in east-central Alberta. (a) Hillshaded relief map (solar azimuth=315°, angle=40°) of the study area, highlighting the association between the hummocky terrain, glaciotectonic terrain (e.g., Flagstaff Hill), and channel systems. Note the dramatic change in channel pattern, orientation and size from Birch Lake to Ribstone Creek. (b) Glaciofluvial channels, interpreted from digital terrain models (DTMs). To facilitate descriptions, glaciofluvial channels have been divided into four geomorphologically distinct zones.

which the channels are eroded.

Contributary and distributary channel linkages are present in many parts of the study area, as part of anabranching patterns, though a parallel pattern is more common, especially in the northern zones. Channel discontinuities in the region are of two types. First, whole assemblages of channels may terminate gradually or abruptly at a topographic feature, usually a high area of hummocky terrain. Second, individual channel segments may be truncated by another, indicating either non-contemporaneous cutting of the segments or abandonment during waning flow.

The character of glaciofluvial channels associated with the Viking Moraine is dependent on the topographic and sedimentologic setting. Because of the variability of channel morphology, I have partitioned the study area into four channel zones to simplify descriptions (Figure 3.3). These divisions were based on variations in topographic expression, pattern, and sedimentary characteristics.

Zone 1

Glaciofluvial channels in Zone 1 occupy a narrow band that climbs over the bedrock-controlled upland of the Viking Moraine along the north and western margins of the hummocky terrain, fading out in the Kinsella area (Figure 3.3). The northern extents of these channels are in the Birch Lake depression. One of these channels dissects glaciotectonic terrain (Figure 3.4). Southward, these channels partly dissect a large upland area herein called the Viking upland. This upland is enclosed by the 700 m contour and extends from Birch Lake to the Sedgewick area (Figure 1.4).

Meltwater channels are arranged in a parallel pattern with few interconnections (Figure 3.4a). The channels that make up this pattern range in size from 200 m to >1 km wide and up to 20 m deep. The parallel pattern persists even where the channels are diverted over part of the Viking upland. Channels tend to be narrower on the upland areas. They are generally sinuous but with some relatively straight segments.

Major channel discontinuities coincide with areas of hummocky terrain. NNW-SSE oriented channels, extending southward from the Birch Lake depression, are succeeded by north-south oriented segments enscribed into the northern slope of the Viking upland (Figure 3.4). Several meltwater channels are cut into low ridges and have convex-up long profiles. Many smaller channels are blind-ended and oriented roughly parallel to the main assemblage. The north-south oriented segments have been truncated by channels that occupy troughs oriented roughly perpendicular to

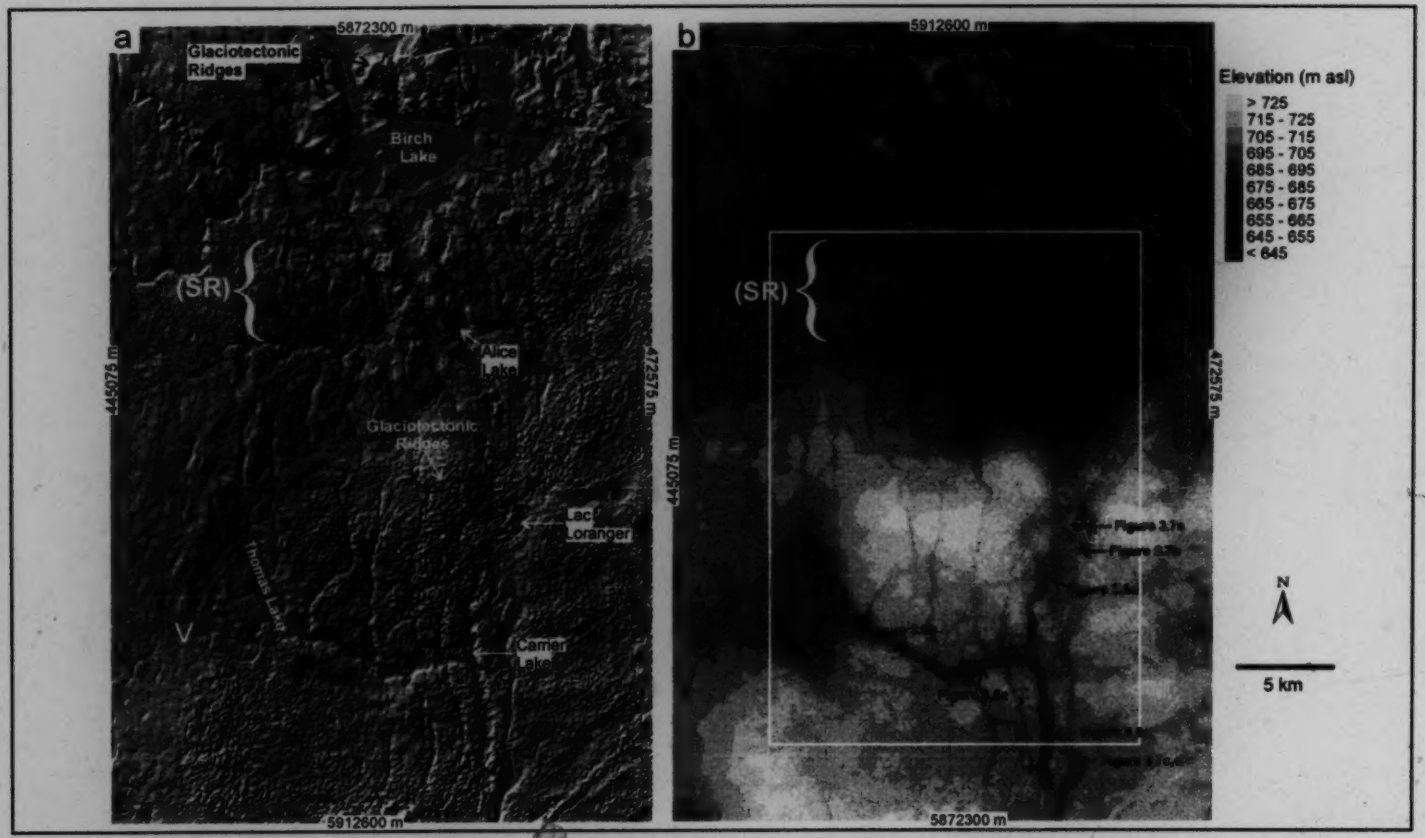

Figure 3.4: Glaciofluvial channels in Zone 1. (a) Hillshaded relief map (solar azimuth=315°, angle=40°). (b) Classed elevation map. Channels south of Birch Lake generally have a NNW-SSE orientation with few interconnections. Some topographic control on channel location is seen where channels are deflected southwards, over hummocky terrain or disappear as they converge on the trough that contains Lac Loranger. Channels converge on reentrants on the northern side of the Viking upland (defined by 700 m contour, Figure 1.4). SR - subtle ridge.

the regional pattern. The best example of truncation is the channel that passes through the Thomas Lake depression, toward Carrier Lake (Figure 3.4).

Three dominant channels extend southward from the Birch Lake depression; one contains Alice Lake. These channels have distinct constrictions and widenings along their length creating a bulbous outline for individual segments. They commonly cut into bedrock and contain substantial glaciofluvial deposits (predominantly sand). Boulder lags rest along the floors of many channels but are more pronounced in channel-bottom depressions occupied by shallow lakes. Many of the constrictions are defined by depositional bars. These channels do not contain hummocks composed of diamicton but the interfluves are capped by diamicton. Smaller channel segments are often isolated and perched above the larger channels or confluent with them. Westward, smaller segments are eroded into bedrock and, occasionally, diamicton. Individual segments are continuous with larger segments, but isolated channels do occur. These shallow channels are eroded into a low-amplitude, east-west trending ridge south of Birch Lake (SR in Figure 3.4). The dominant channels have completely dissected this ridge which is slightly undulatory, with the shallow channels supplying most of the relief. East of Alice Lake, several narrow segments breach the same low-amplitude ridge, but are associated with hummocky terrain. They are roughly parallel, with only a few channel linkages, and deflect toward the Lac Loranger trough. These channels maintain their width and depth along their length, even though some appear to have been diverted around and over higher terrain.

Along the northern slope of the Viking upland the orientation of channel segments shifts, adopting a north-south orientation. These channels pass over the high terrain of the upland and into the east-west trough to the south (Figures 3.4 and 3.5). Continuous channels crossing this rise have been deflected by minor topographic elements. Some segments are discontinuous on the higher portions of the upland, giving way to high-relief hummocky terrain. Channel floors closer to Lac Loranger are more hummocky and indefinite than those closer to Thomas Lake. In some locations they are little more than hummocks at lower elevations than the surrounding terrain. The elevation gain over this upland is approximately 30 m, whereas the relief between channel thalwegs and margins does not exceed 10 m (Figure 3.5). Even though the channels locally have hummocky thalwegs, at a larger scale they have pronounced convex-up long profiles. Channel morphology changes little over the rise, maintaining relatively consistent widths (approximately 300 m), but with more variable depths. The depths of the channels are intimately linked with the density of hummocks; where adjacent hummocks are higher, channel thalwegs are more variable.

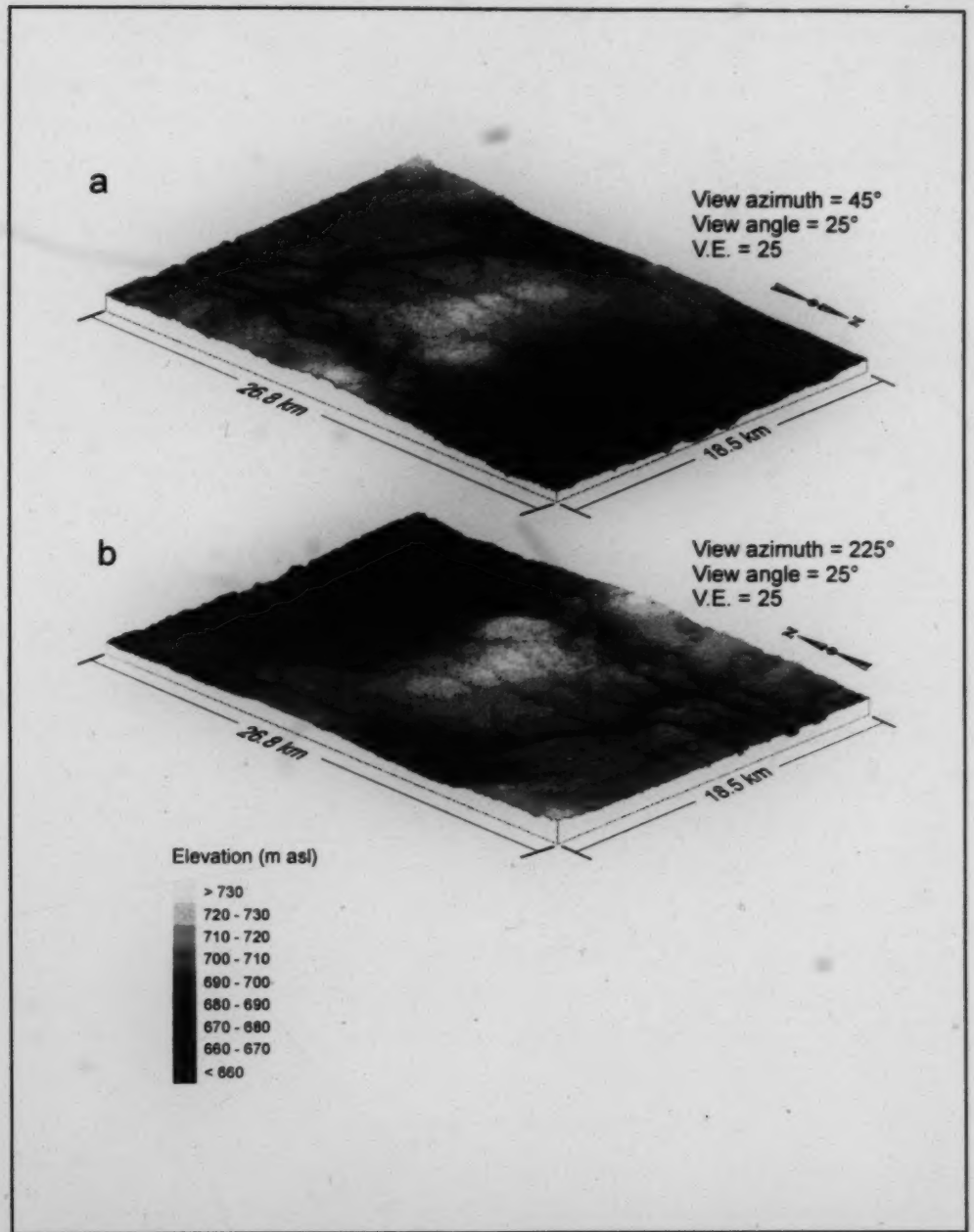

Figure 3.5: Perspective views of glaciofluvial channels that are continuous over a significant topographic high. (a) View from 45° showing the steeper slope of the northern part of the Viking upland with the sinuous outline where channels are funnelled into reentrants. (b) View from 225° showing the continuity of the channels as they pass through the depression and up the next rise. See Figure 3.4b for area locations.

The Viking upland is dominated by hummocky terrain, composed of glacial sediment overlying bedrock. Glacial sediments are usually thick, but some depressions contain exposed bedrock. Also, the presence of saline sloughs indicates that bedrock is close to the surface in many locations. Where exposed, bedrock often shows little evidence of disturbance (Figure 3.6a), though some exposures attest to more intense glaciotectonic activity (Figure 3.6b). Where bedrock dominates channel margins, the slopes are relatively steep. Channels cut into diamicton have a more subtle expression. Channel interfluves dominated by bedrock are commonly capped with thin diamicton beds (Figure 3.6c). Perched glaciofluvial deposits are also commonly present near the crests of these interfluves, mantling the diamicton. These minor deposits are located above the diamicton-bedrock contact and at the location of Figure 3.6c are found on both sides of the channel. In hummocky terrain, bedrock exposures are often associated with boulder lags that are common in the depressions and to a lesser extent on the hummocks themselves (Figure 3.6d). The presence of boulder lags and saline sloughs eroded into bedrock indicates that fluid erosion/winnowing of glacial sediment and scouring of the underlying bedrock have been crucial in the formation of the channels and hummocky terrain, after the emplacement of the diamicton (till). This simple observation is at the heart of the genetic interpretation of the regional landform associations discussed in Chapter Five.

Although there are occasional glaciofluvial deposits on higher terrain, most are located in one north-south oriented trough (the Lac Loranger trough) that dissects the Viking upland. Glaciofluvial sediments are highly variable in texture and architectural style (Figure 3.7). Poorly-sorted, cobble-gravels and boulders are found closely associated with well-sorted sands and pebbles. There is little indication of downflow (southward) fining because some of the finest sediments are found in the upper (northern) reaches. In the vicinity of Lac Loranger, glaciofluvial deposits range from cobble gravel arranged in broad, arching beds (Figure 3.7a) to cross-bedded coarse sands with secondary cross-laminated, fine sands and silts (Figure 3.7b). These two adjacent sites are at approximately the same elevation on opposite sides of the poorly defined channel. Paleocurrent estimates from each site indicate that flow converged toward the channel axis (generally southward). Downflow of these two sites, sediment is better sorted but generally coarser. Typical sediment in this channel includes clast-supported gravels with a secondary component of matrix-supported, pebbly-gravels (Figure 3.7c). In addition to this dominantly cobble to sand component, large boulders (>1 m in diameter) are common (Figure 3.7d). These boulders range from rounded to

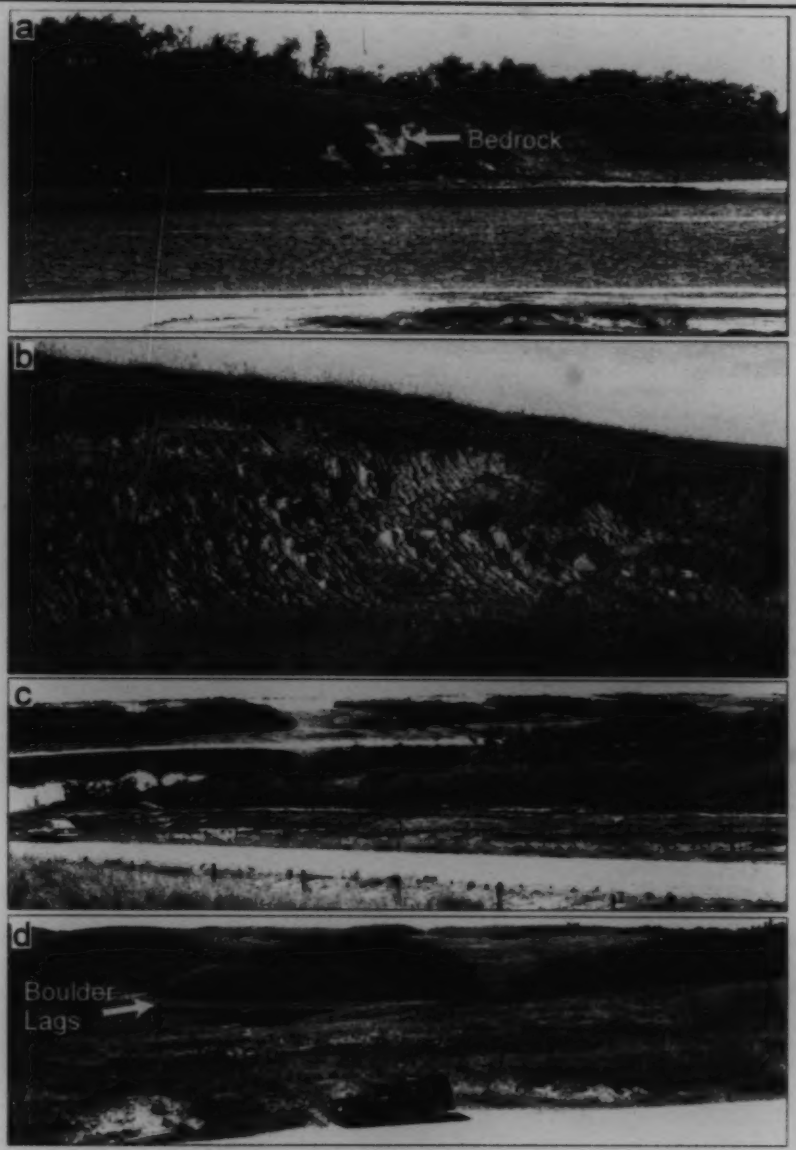

Figure 3.6: Bedrock occurrences in the northwest portion of the Viking upland. (a) Bedrock hummock in the Thomas-Carrier Lakes channel. The bedrock is questionably *in situ*. (b) Glaciotectonized bedrock along the southern slope of the Thomas-Carrier Lakes channel. (c) Ridge along the eastern margin of Carrier Lake. A thin diamicton cap (~4 m) overlies *in situ* bedrock. (d) Hummocky terrain north of Carrier Lake has boulder lags on and between hummocks. Alkaline sloughs and limited bedrock exposures along the slopes of the hummocks indicate that the bases of the depressions are below the bedrock contact (approximately at the truck).See Figure 3.4b for area locations.

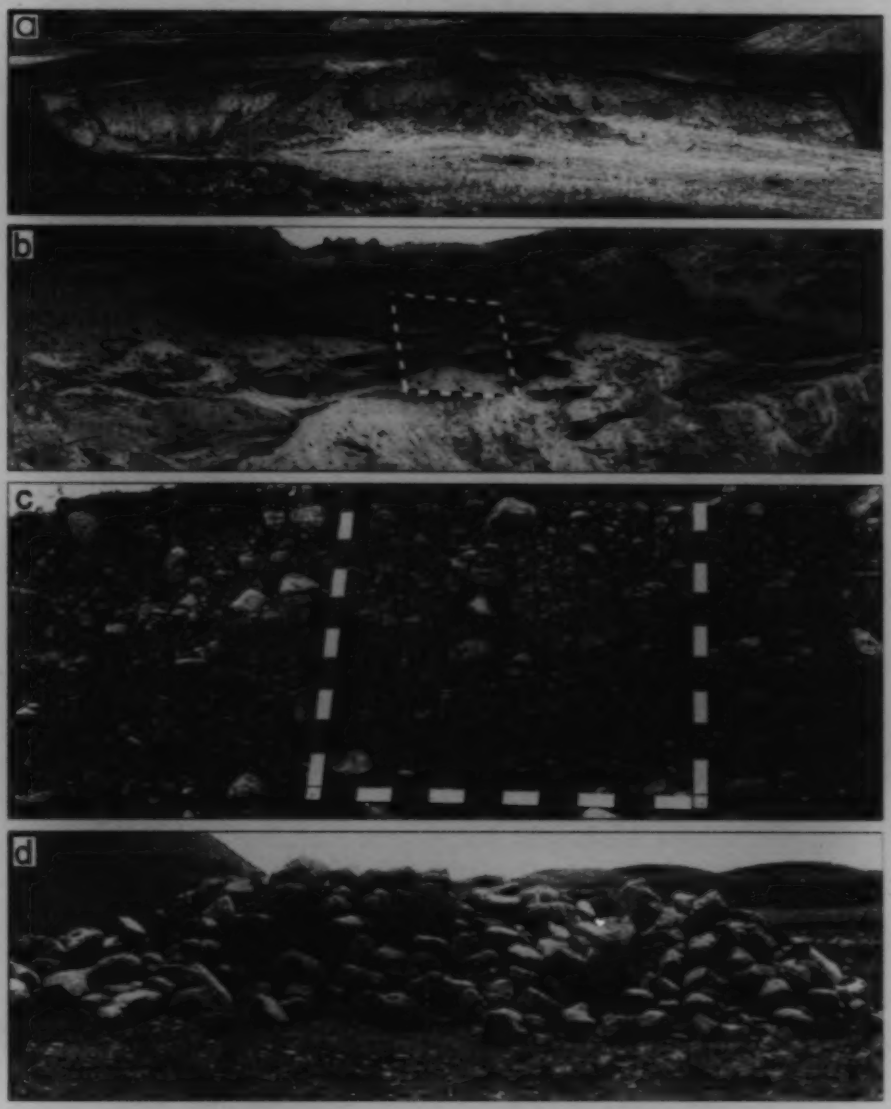

Figure 3.7: Glaciofluvial sediments in the Lac Loranger trough. (a) Cobble gravel southeast of Lac Loranger. The gravel is primarily planar-bedded with minor occurrences of cross-bedding. The gravel beds form a broad anticlinal architecture that roughly parallels the surface of the landform. Paleocurrents are highly variable but tending toward the SSE. (b) Plane and cross-bedded sands southeast of (a). Sands are well-sorted, upward-fining with some fine-grained intraclasts and pebbles along bounding surfaces. (c) Clast- and matrix-supported gravels in a well-defined channel. (d) Oversized clasts in the same pit as (c). Note the quadrat is 1 m^2 with decimetre divisions. See Figure 3.4b for area locations.

angular and striated facets are common, indicating that those clasts travelled only short distances in glaciofluvial transport.

Glaciotectonically modified terrain is present throughout the study area but is less evident in Zone 1 (Figure 3.3b). In this area a few well-defined ridges north of Birch Lake have been truncated by glaciofluvial channels. On the northern flanks of the Viking upland several arcuate, low-amplitude ridges are truncated by the channels and appear to have obscured the hummocky terrain (Figure 3.4). The superimposition of the channels, with convex-up long profiles, on the glaciotectonic ridges (which in turn are contemporaneous or postdate hummock formation) indicates the sequence of events that formed the landscape in this region.

Zone 2

Channels are oriented northwest-southeast and have a sub-parallel pattern, though some interconnections occur at acute angles producing a poorly-developed anabranching pattern (Figure 3.8). These channels have been interpreted as "stream trenches" formed in ice-walled channels (Gravenor and Bayrock 1956). Part of this channel system is diverted northward, connecting with Grattan Creek where it encounters a high area of hummocky terrain. A few segments are continuous with Zone 3, eventually linking with the Hardisty basin (Figure 3.3b). Only a few channels that enter the Kinsella basin are continuous with the main outlet (Grattan Creek). Channels in Zone 2 are roughly parallel to Grattan Creek, though southward they deflect toward the Hardisty basin (Figure 3.3b).

These channels do not conform to the topography entirely, but originate on the southwest flanks of the Viking upland, pass through a NNW-SSE oriented depression (695 m contour in Figure 3.8), climb over higher ground and join other channels to the southeast (Figure 3.8b). Channels begin abruptly in the western part of the Viking upland, characterized by moraine plateaux and high relief hummocky terrain. At these locations, channels have narrow, indistinct outlines and seem to merge into the hummocky terrain. At the origin of one channel there is a small, triangular-shaped moraine plateau (MP in Figure 3.8a). None of these channels contains overdeepened portions, in headward locations, that could be described as plunge pools. Hummocky terrain in the area is not confined to the higher ground, but is also found within the NNW-SSE oriented, broad depression. Channels that connect with Zone 3 are oblique to this broad depression, and cross-cut the channel that occupies the lowest ground (Figures 3.3b and 3.8). The main group of channels terminates abruptly at a high

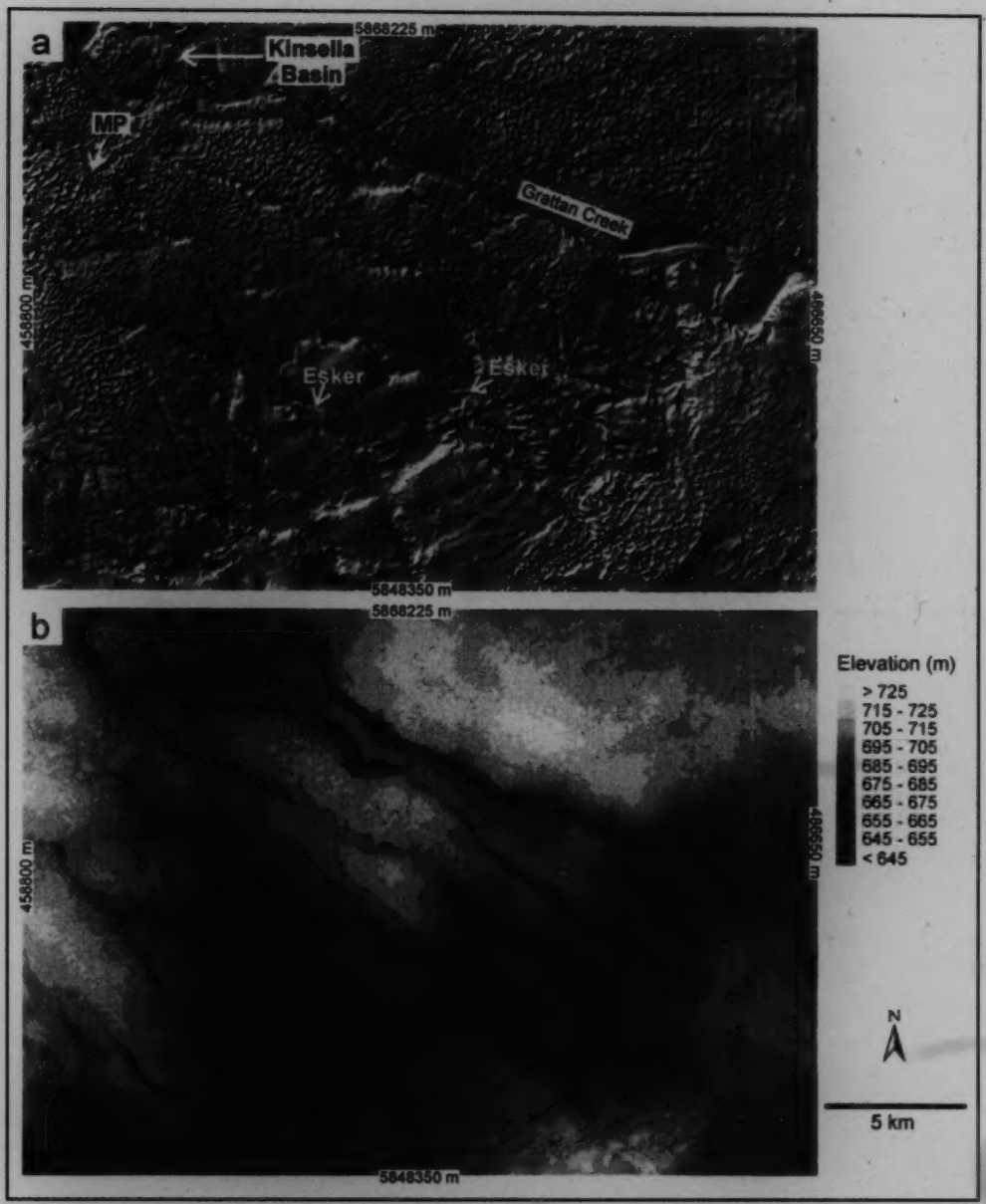

Figure 3.8: Glaciofluvial channels in Zone 2. (a) Hillshaded relief map (solar azimuth=315°, angle=40°). (b) Classed elevation map. Glaciofluvial channels are oriented roughly NW-SE and start in hummocky terrain or as a continuation of the Kinsella basin. Channels in high relief hummocky terrain are little more than aligned depressions, whereas scarp forms dominate where the hummocks are more subdued. Note that several channels are oriented oblique to the topography and possess undulatory paths that have greater relief than the relief within the channel.

area of hummocky terrain in the southeast, although there is a northward connection with Grattan Creek. This high zone of hummocky terrain contains curvilinear ridges and oriented hummocks. Channels that encounter this higher area terminate roughly perpendicular to the orientation of the ridges within the hummocks. Within this hummocky zone there is one small moraine plateau. Where a saddle in the hummocky terrain exists the channels seem to penetrate further into the hummocks. Glaciofluvial deposits are common, interspersed with the hummocky terrain and significant glaciofluvial landforms and sediments are present southwest of this hummocky area.

There is a continuum of channel forms in the area, ranging from those defined by a series of linked hummocks to well-defined scarp forms (Figure 3.9). Subtle transitions that occur along individual channel segments reflect geologic, topographic and/or hydrodynamic control(s) which influenced the resulting forms. Most of the transitions between hummocky and scarp forms are coincident with a change from high relief hummocky terrain to more subtle, undulating topography. This subtle topography is associated with scarp forms because the thickness of glacial material (primarily till) is significantly less than in high-relief hummocky terrain. Contributary channel junctions indicate either contemporaneous or non-contemporaneous formation of channel segments. Contemporaneous occupation of channels is indicated by contributary junctions that do not exhibit truncation or backwater sedimentation. If some channel segments preexisted, there should be obvious truncation and backwater deposits similar to those found in the Channeled Scabland of Washington State (e.g., Smith 1993). Large scours at contributary junctions and channel segments that continue past these junctions indicate that there was some truncation of older channel segments. Cross-cutting relationships indicate that not all channel segments are contemporaneous, though this tends to be the exception (Gravenor and Bayrock 1956).

Channels with shapes transitional between hummock-floored and scarp forms have scalloped margins with low-relief intrachannel hummocks. In Figure 3.9a the scalloped margins are apparent and, rather than distinctive hummocks along the bottom of the channel, there are cusp-shaped areas of higher ground that connect the channel margins at narrowest points. Transitions from aligned depressions to indistinct channels are accompanied by a change from intrachannel hummocks that have concordant tops (with the surrounding hummocky terrain) to those that are depressed below the adjacent interfluves. Where the channel margins are less distinct, channel widths and depths are significantly smaller. The configuration of most hummocks in channels appears to be associated with formation of the channel. However, in some locations hummocks

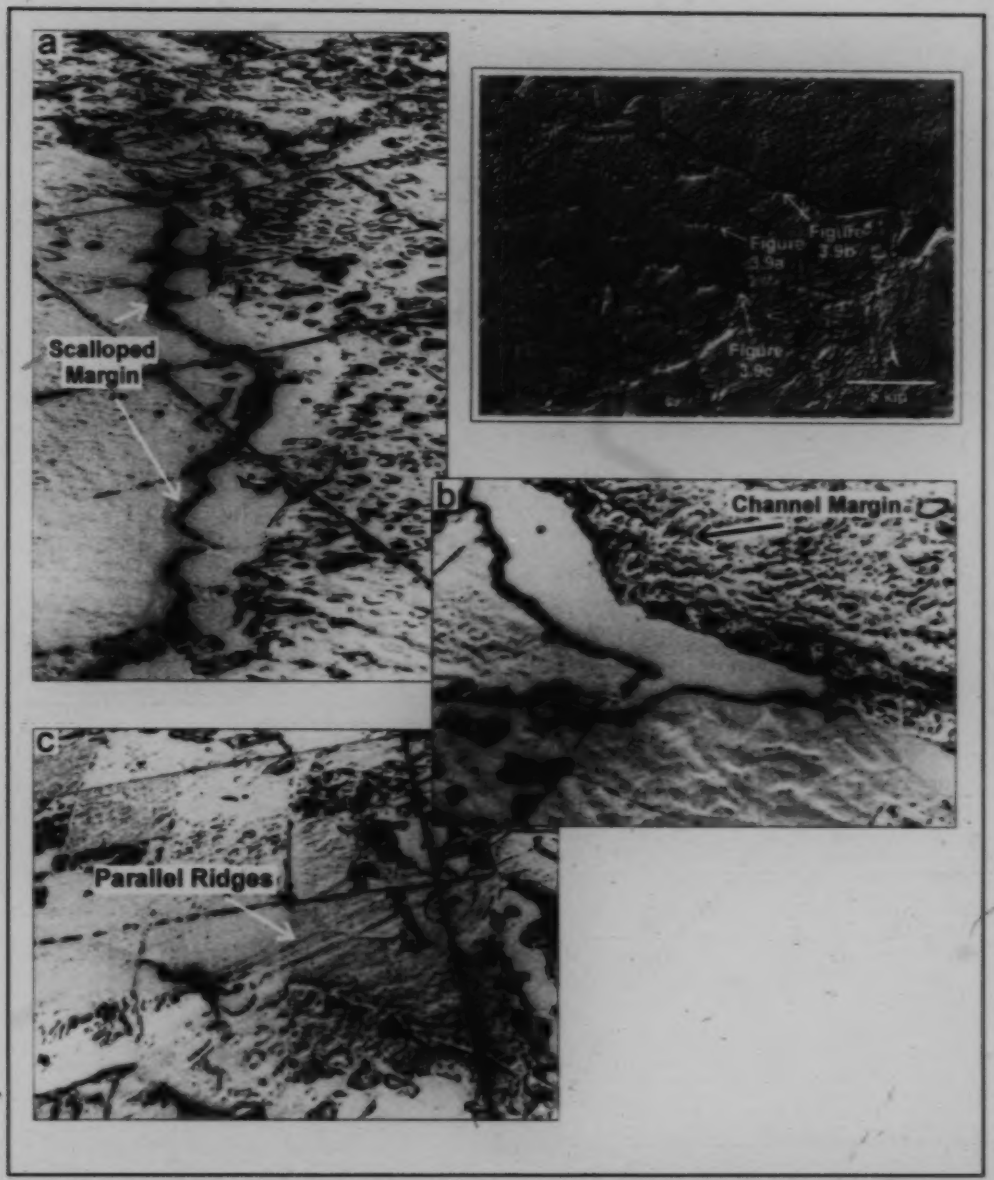

Figure 3.9: Glaciofluvial channels in Zone 2. (a) This deeply scalloped channel margin is associated with cuspate areas that subdivide the channel into a series of linked potholes. The cuspate dividers are only a few metres high, with the lowest point in the middle of the channel. Note the contrast of the hummocky area to the north (right) and subdued terrain to the south of the channel. (b) Former margin of the channel mantled with hummocky terrain. This hummocky terrain apparently has diverted the channel to the south (left). (c) Scarp form of channels in the southeast portion. The scarp form is maintained by the presence of bedrock near the surface. Note the hummocky terrain and the parallel ridges on top. Photos courtesy of J. Shaw.

appear to mantle a preexisiting channel floor (Figure 3.9b). Numerous boulder lags and alkaline lakes/sloughs are associated with these indistinct channel segments. Boulder lags are present on hummocks (both inter- and intrachannel) and in the intervening depressions. Saline lakes/sloughs are common in the intrachannel depressions and interhummock depressions.

Scarp form at the other end of this morphological continuum are characterized by very sharp transitions between the interfluves and steeply sloping channel margins (Figure 3.9c). These steeply sloping margins are preserved because channels were cut mainly into Cretaceous bedrock. In some locations the bedrock has been disturbed glaciotectonically. Rills cut into channel slopes indicate the presence of bedrock. In areas where the scarp forms are present bedrock is exposed at the surface or is covered by only a thin veneer of glaciogenic sediment. The scarp-form channel bottoms are relatively flat and wide compared to the indistinct channels. Bedrock is commonly exposed beneath an extensive boulder lag along the bottoms of the channels. These distinct, scarp-form channels often contain glaciofluvial sediments, including eskers, whereas indistinct forms usually have limited glaciofluvial deposits.

Intrachannel topography is produced by erosional and constructional landforms, dominated by hummocks (Figure 3.10). The composition of these hummocks is usually the same as hummocks found on the adjacent interfluves. Where hummocks are composed of diamicton (Figure 3.10a), the matrix is usually compact, clayey (silty-sand sediments are present), and relatively clast-poor. In addition to diamicton, some hummocks are composed of Cretaceous bedrock (Figure 3.10b). Generally, bedding in bedrock hummocks is approximately horizontal, though there are locations where the bedrock has been displaced. There is also evidence for slumping of bedrock along the sides of the channels. The slump blocks are readily apparent and sometimes give a hummocky appearance to the channels. However, bedrock hummocks in the middle of the channels (up to 1 km across) cannot be attributed to slumping activity but are clearly erosional forms. Generally, where bedrock is exposed in the channel, the floor is flat and the margins steep.

In some locations intrachannel landforms are depositional types, such as gravel and sand hummocks, eskers containing gravel and sand, and boulder accumulations (differentiated from boulder lags on the basis that accumulations are greater than one clast thick). The main sites (Figure 3.11) for gravel and sand accumulations are located at channel expansions, particularly at contributary junctions of several channels. The most prominent depositional zones are the Kinsella and Hardisty basins (Figure 3.3b). Secondary sites for gravel and sand accumulations occur within

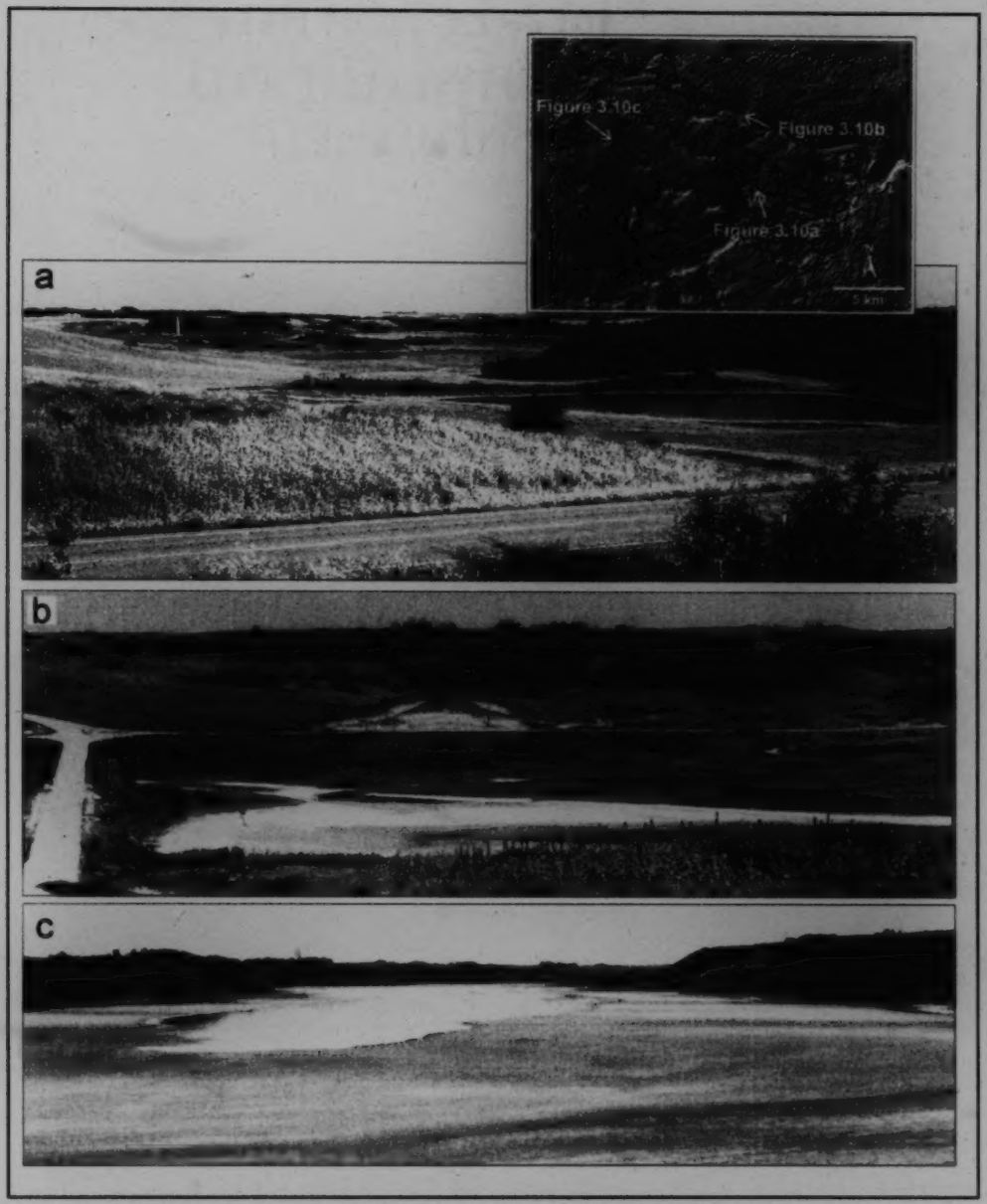

Figure 3.10: Morphology of channel bottoms in Zone 2. (a) Channels with hummocky floors are usually gently undulatory, with the amplitude of hummocks mimicking the relief of hummocky terrain adjacent to the channels. The hummocks are usually composed of compact diamicton, similar to those hummocks on the interfluves. (b) Hummocks composed of Cretaceous bedrock are also present. Some of these bedrock knobs may be attributed to postglacial slumping, but others are *in situ*. (c) Channel floors with exposed bedrock are more commonly flat-bottomed. Note the steep channel margin that exhibits minor postglacial slumping.

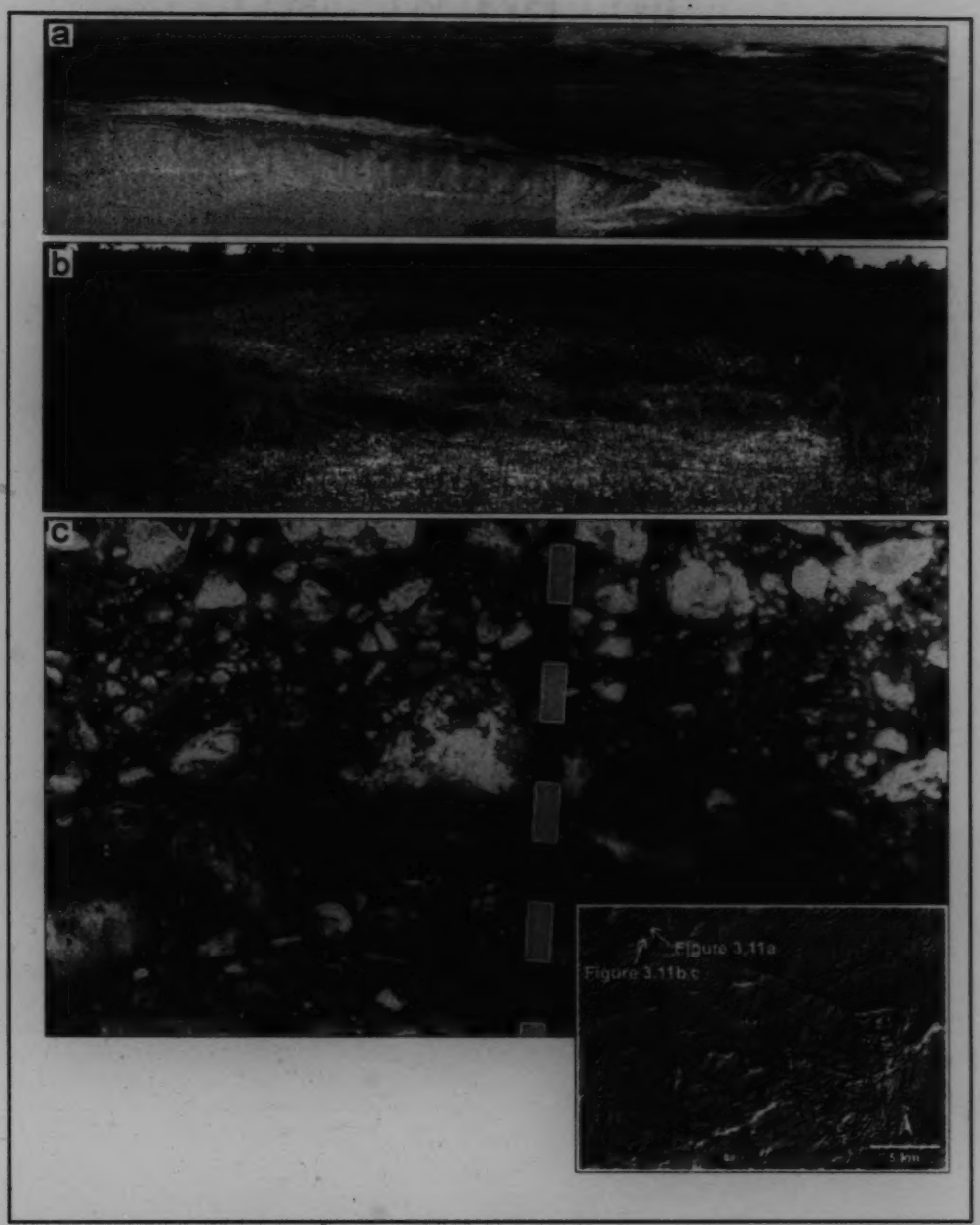

Figure 3.11: Major glaciofluvial deposition associated with channels in Zone 2. (a) Southern part of the large expansion bar in the Kinsella basin. Sediment texture is highly variable though at this location moderately well-sorted dipping beds roughly parallel the surface topography. (b) Glaciofluvial hummock in a channel adjacent to the Kinsella basin. Note the armour of boulders. (c) Multimodal gravel contained in the hummocks. Note how the fabric of the smaller clasts closely mimics the shape of the boulder (centre).

channels at pronounced flow expansions. Depositional landforms may be in the form of large point bars and expansion bars. Figure 3.11a illustrates the large-scale cross-stratification present in sediments along the southern side of the Kinsella basin. Here the cross-bedding indicates flow toward the east-southeast though in other locations such indicators are highly variable. The sediment ranges from well-sorted sands and gravels to poorly-sorted, heterogeneous units of fine sand and boulders. In addition to the expansion and point bar deposits, some channel deposits (Figure 3.11b) are morphologically identical to hummocks composed of diamicton. The poorly-sorted sediment in these hummocky landforms range from sand to boulders (Figure 3.11c). Generally, bedding is absent, apart from a poorly-defined fabric of smaller clasts on the underside of some larger boulders (Figure 3.11c). This mimicking of the shape of the boulder with the smaller clasts is likely related to slumping.

Occasional eskers associated with other glaciofluvial deposits within the channels. They are aligned down the axis of channels, found along the edge of channels, or cross at high angles. These eskers are relatively small in comparison to other examples in the literature (Banerjee and McDonald 1975; Brennand 1994), reaching only a few metres from base to crest. Their crestlines in longitudinal profile tend to be undulatory but in some eskers this characteristic is subdued. Eskers are usually continuous, isolated, segments with rare discontinuities along an individual segment. They are nearly always single-crested with some multiple-crested systems (Figure 3.12a and c). Eskers are found in three settings additional to the main glaciofluvial channels: (1) in troughs that are incised into an expansion bar deposits that represent major depositional zones; (2) adjacent to and superimposed on hummocky terrain; (3) resting directly on bedrock and flanked by boulder lags.

One esker is aligned transverse to the orientation of the channels and is relatively continuous through the channels and over the interfluve (Figures 3.12a and b). In this area the channels have large hummocks along their floors and are discontinuous a few hundred metres to the northwest. The esker is situated in a shallow depression as it crosses the interfluves and is slightly sinuous (Figure 3.12b). As illustrated by Figure 3.12a, the esker crosses an interfluve (A), continues through a channel (B), crosses a second interfluve (C) where it breaks down into a net, crosses a second channel (D), crosses another interfluve (E), and finally connects with a hummocky-floored channel that slopes to the southeast. The esker ridge is not continuous over its entire length but rather forms a distributary net (C) with minor discontinuities along its length. This may be interpreted as a high pressure zone where lifting of the ice allowed distributary channels to form. The esker crosses interfluves which are approximately 5-7 m high, whereas the esker ridge itself is only 3-4 m high.

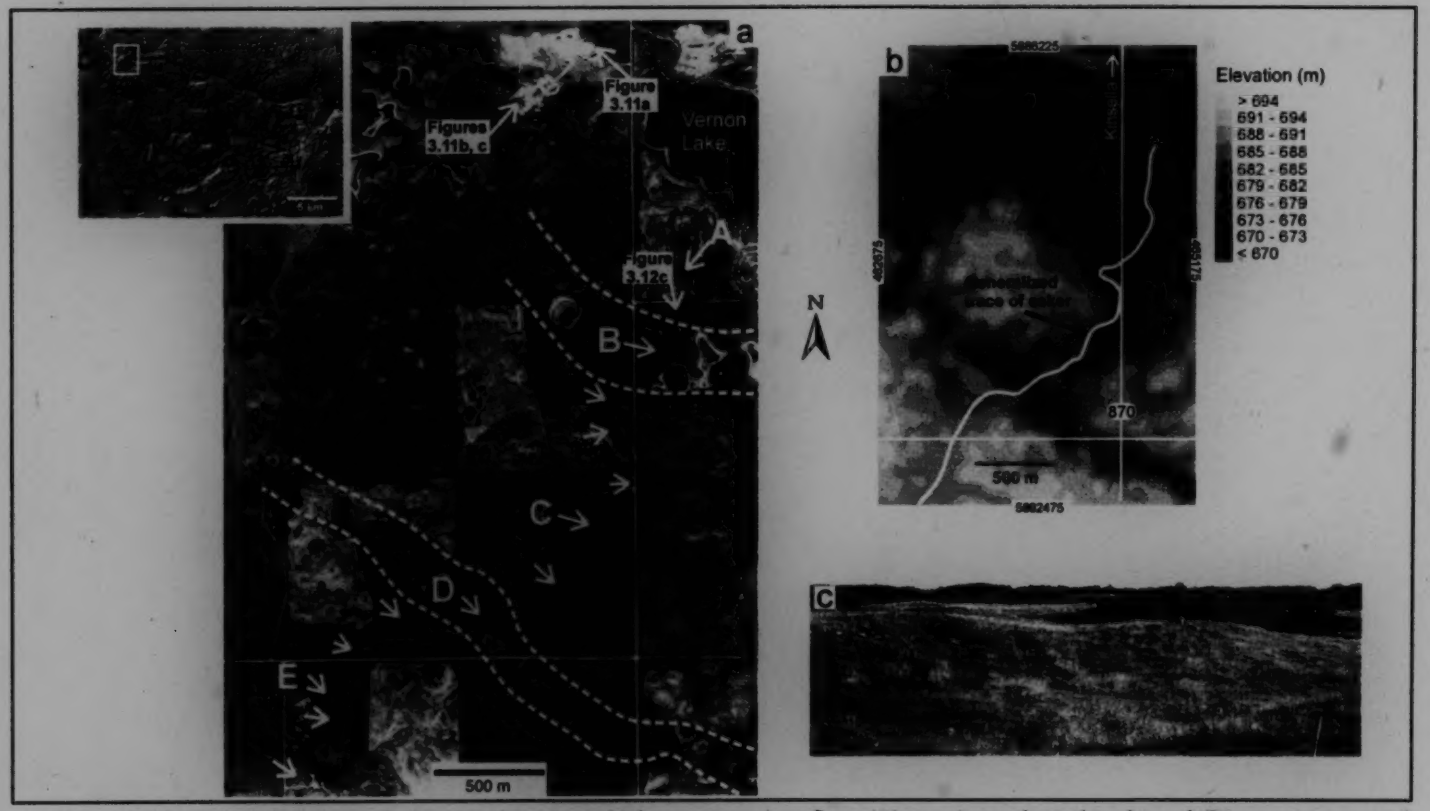

Figure 3.12:(a) Aerial photograph showing the esker which crosses an interfluve (A), continues through a channel (B), crosses a second interfluve (C) where it breaks down into a net, crosses a second channel (D), crosses another interfluve (E), and finally connects with a hummocky-floored channel that slopes to the SE. The esker ridge is not continuous over its entire length but rather forms a distributary net (C) with minor discontinuities along its length. (b) Classed elevation map showing the generalized trend of the esker. Note the shallow trough it occupies as it crosses the interfluves. (c) Undulatory crestline of the esker near its northern end. The crest of the esker, as it crosses the channel, is below the adjacent base of the esker, indicating that it formed subglacially.

This characteristic requires that either the formative environment was subglacial and under pressure or that the it was let down on the landscape by meltout. In either case the esker clearly postdates formation of the other landforms including the hummocky terrain. The small size of these eskers can be attributed to the small catchment available and indicates a poorly integrated glaciohydrologic system.

Zone 3

Glaciofluvial channels in Zone 3 (Figure 3.3) are characterized by large, well-defined segments, compared to Zones 1 and 2 (Figure 3.13), and have imparted a highly dissected nature to the area. Channels are usually 300-500 m wide and range from nearly imperceptible, to 35 m deep. An irregular anabranching pattern dominates, although a rectangular pattern is present south of Flagstaff Hill (Figure 3.13). Channels originate along a gently curving topographic high running from Sedgewick to Hardisty. The northern ends of these channels merge with the trough that sweeps through the Sedgewick area. These segments are well-defined for most of their length. One channel is oriented roughly perpendicular to the general trend and appears to truncate other channels and residuals. The channels surround some of the higher terrain elements and thus have dissected the upland into irregularly shaped residuals. The lack of a consistent channel patten indicates that the factors controlling the formation of the channels were complex.

Channels in Zone 3 are situated on an upland flanked by the Hardisty basin to the northeast, the Bellshill Lake depression to the west, and Flagstaff Hill to the southwest. This subtle upland is straddled by many glaciofluvial channels with few connections to the south and southeast side of the Battle River valley. The location of the channel system is intriguing because it does not completely conform to the topography. Several channels have convex-up long profiles, though this convexity is not usually pronounced (Figure 3.13b). Rather, long profiles are undulatory, with intrachannel relief on the order of 10-20 metres. Terrain northwest of Bellshill Lake (Figure 3.13) is incised by relatively small, low-sinuosity channels compared to those that dissect the higher ground northeast of the lake.

The nature of channel interconnections, and near absence of truncation, indicates that the channels operated contemporaneously. In several locations, perched saddles link the main channels whereas in others small, narrow channels provide linkage (Figure 3.14). These perched segments often have a hummocky appearance. In addition, there are several indistinct channel segments, across the large residuals, that may have linked the channels at one time. Generally, confluent

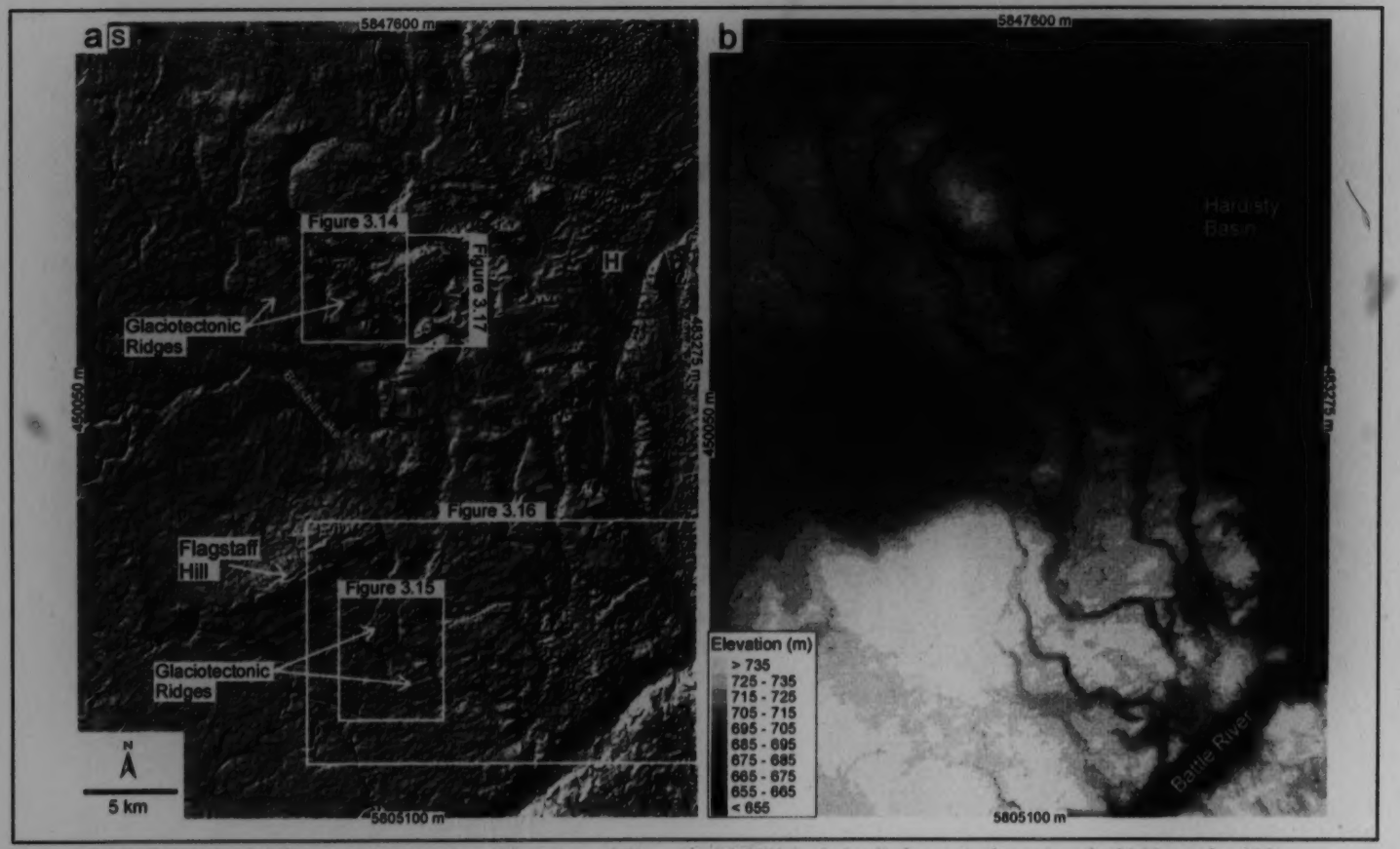

Figure 3.13: Glaciofluvial channels in Zone 3 and location of Figures. (a) Hillshaded relief map (solar azimuth=315°, angle=40°). (b) Classed elevation map. Glaciofluvial channels have dissected the upland from an escarpment which trends from Sedgewick (S) to Hardisty (H). The channels are associated with glaciotectonic ridges and to a lesser extent hummocky terrain. Where glaciotectonic ridges have been dissected by the channels there appears to have been a significant control on channel morphology and location.

Figure 3.14: Stereotriplet showing the morphology of channels in the vicinity of Beyers Lake. Channels have numerous lakes along their floors which are controlled by different shapes of hummocks. Bedrock is exposed along some channel floors. Most channels in this area are sinuous with linkages that may be perched, broad saddles (S), narrow breaches (N), or conformal. Hummocky terrain superimposes perched segments in places. Glaciotectonic ridges are present on the interchannel residuals. Note the perched, linear channel (PLC).

channels have coincident thalwegs. Interconnections occur at various angles and appear to be associated with the preexisting topography rather than a hydrodynamic response.

Channels south of Flagstaff Hill include both straight and sinuous segments (Figure 3.15). The rectangular system of channels connects with the main anabranching channels. The relatively straight segments that comprise this rectangular pattern are narrow and shallow, seldom exceeding 250 m in width and 5-10 m in depth. These channels contain lakes along their thalwegs. Channel interconnections are usually conformable but perched, blind-ended channels are present. Shallow saddles on the interfluves may have operated as channel linkages at an earlier stage of development. These channels are cut into diamicton (presumably till) though bedrock outcrops at a few locations.

Intrachannel relief may be attributed to several processes. Lakes, that commonly occupy the channels, are separated by either erosional remnants or depositional landforms. The lakes appear as potholes and are often saline, suggesting the marine bedrock is near/at the surface in many locations. Intrachannel hummocks may contain gravel, sand, and/or diamicton. Boulder lags are common within and along channels as well as on hummocky terrain. In several locations, slumping of the channel margins has created ridges on channel floors. The oversteepening of channel walls presumably was due to the rapid incision. Although channel margins have slumped, it is not possible that all the intrachannel relief results from this process. In some cases the channel walls are only marginally higher than the height of the hummocks along the channel floor and the channels are often greater than 500 m across. It would be difficult to backwaste channel margins without significant slope.

Hummocky, intrachannel elements merge, imperceptibly, with hummocky terrain. One of the best examples of this is in the southeast portion of Zone 3, near the elbow of the Battle River (Figure 3.16). All the channels in the area are connected to this hummocky zone. Continuity between hummocks within the channels and a field of hummocky terrain is accompanied by a general rise in elevation and disappearance of the channel margins. Where the channels connect to this hummocky zone, the elevations of the thalwegs are below the hummocky terrain. This is particularly apparent at A and B in Figure 3.16. The residual uplands between the channels at this contact commonly have superimposed linear ridges. These residuals seldom carry hummocks but hummocks are prevalent on the upland rising above the channel interfluves. Superimposed ridges appear to have been continuous with ubiquitous arcuate ridges. Generally, these ridges are perpendicular to the channels at this location. At the contact with the channels, the hummocky terrain is restricted to the lower ground, flanked on the east by an upland that separates it from the Battle River valley. The

Figure 3.15: Stereotriplet illustrating the transition between rectangular and sinuous channels in the southern part of Zone 3. Hummocks are common along the bottom of the channels. Rectangular channels have narrow lakes along their floors with lower hummocks than the sinuous segments. These channels are discontinuous with some perched, isolated segments. Note that the confluences of rectangular and sinuous segments appear to be conformal rather than truncated. Glaciotectonic ridges are roughly perpendicular to the channels and in places appear to have controlled the location and morphology of the channels.

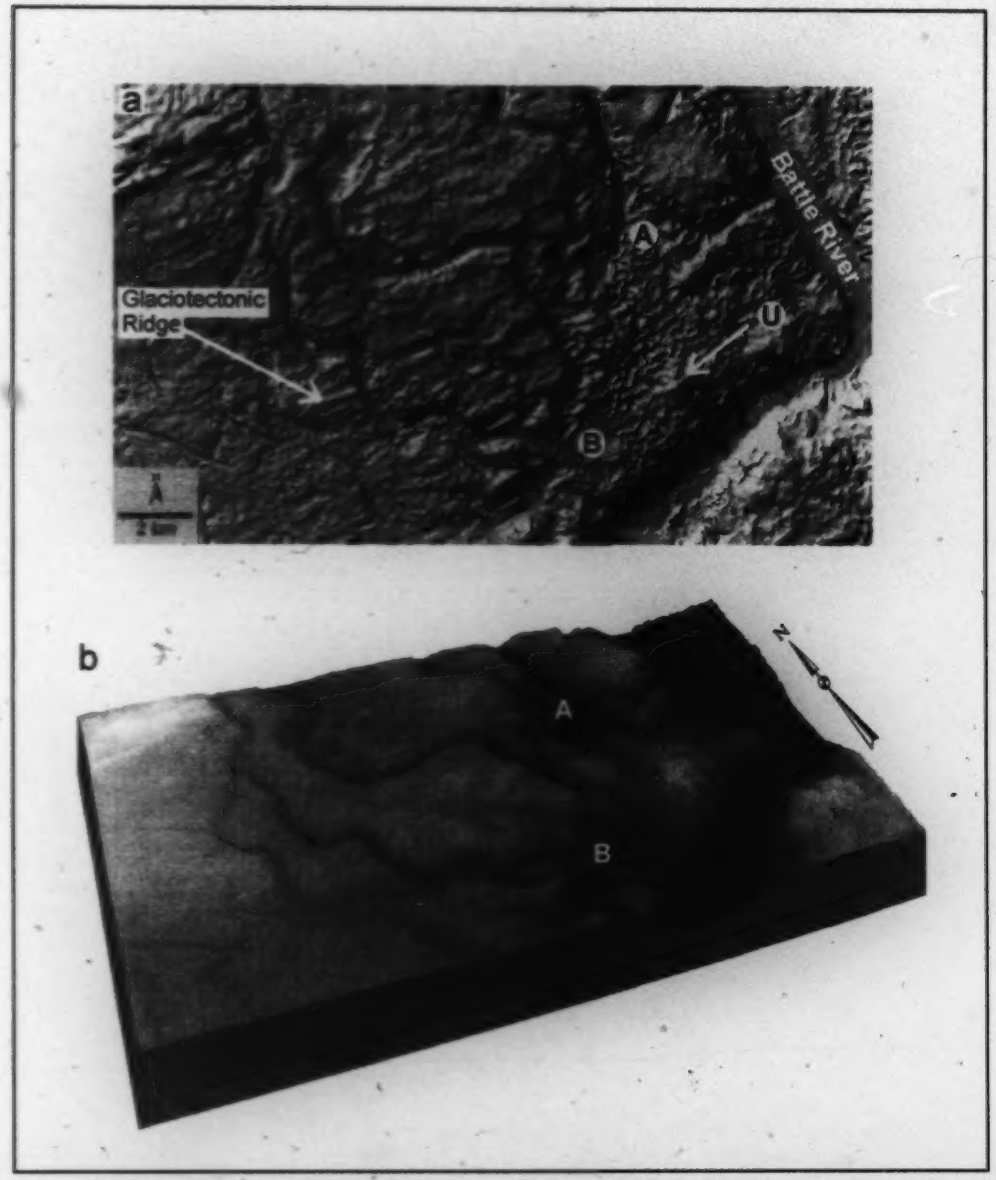

Figure 3.16: Juxtaposition of channels in the southern part of Zone 3 and hummocky terrain. (a) Hillshaded relief map (solar azimuth 315°, angle 40°). (b) Perspective view with a continuous grey scale drape of elevation. All the channels of Zone 3 converge on a field of hummocky terrain which slopes up to an upland (U). In the northern part of the hummock field, the hummocks occupy the channels but not the adjacent higher ground. The interchannel residuals have perpendicular ridges (glaciotectonic). This hummock field extends into Zone 4 (south of the Battle River). Note the undulatory thalwegs of the channels and the low basins at A and B where the channels encounter the hummocky terrain.

hummocky terrain rises to the south, forming a high zone adjacent to the river. This topographic high extends south of the river and has apparently been breached by incision of the Battle River.

In most locations the sediment contained in landforms along the bottoms of channels is composed of either diamicton (usually till) or glaciofluvial sediment. Boulder lags are common throughout the area but are not pervasive. The observation that constructional and erosional landforms occur within the channels is critical to interpreting the formative environment. In the central portion of Zone 3, a southwest-northeast oriented channel appears to have truncated the generally northwest-southeast trend of channels in the area. Junctions of the channel thalwegs are conformable. Within channels there are a number of elements including hummocks, slumps, and erosional remnants. One large erosional remnant in the centre of the channel contains *in situ* preglacial gravels (Figure 3.17). The sediments at this site are considered preglacial because they do not contain shield clasts. Note the small boulder of shield origin resting on the preglacial gravels. The preglacial sediments include coarse sand to pebbles that are well-sorted, primarily plane-bedded, and rounded to well-rounded. No postdepositional disturbances such as faulting, ice-wedge-pseudomorphs, or loading structures were observed. The erosional remnant that contains the preglacial gravels cannot be associated with a subsequent erosional episode since, even though the flanking channels look truncated, their thalwegs are conformal (Figure 3.17a).

Zone 4

Glaciofluvial channels, on the south side of the Battle River, have a parallel pattern of discontinuous channels that are confluent with Ribstone Creek (Figure 3.18). Channels are oriented northwest-southeast. There are some dendritic sections, but these are relatively insignificant. Channels are confluent with Ribstone Creek in the southeast corner of Figure 3.18. Ribstone Creek flows northward, roughly parallel to the Battle River, through the Wainwright area (not shown). Channels in this zone are not as large as in the others; usually less than 15 m deep and 450 m across. The channel pattern and morphology are closely related to the topography of the area.

Channels in Zone 4 are bounded on the northwest by the Battle River and on the southeast by Ribstone Creek. Between these larger systems lies an upland that is a continuation of the upland hummocky terrain from Zone 3. This interfluve between the Battle River and Ribstone Creek is broad with many undulations imparted by glacial and preglacial fluvial processes. Generally, the land slopes toward the northwest, although the undulatory character of the terrain obscures this trend. Channels in this zone occupy an indistinct trough forming a saddle through the interfluve.

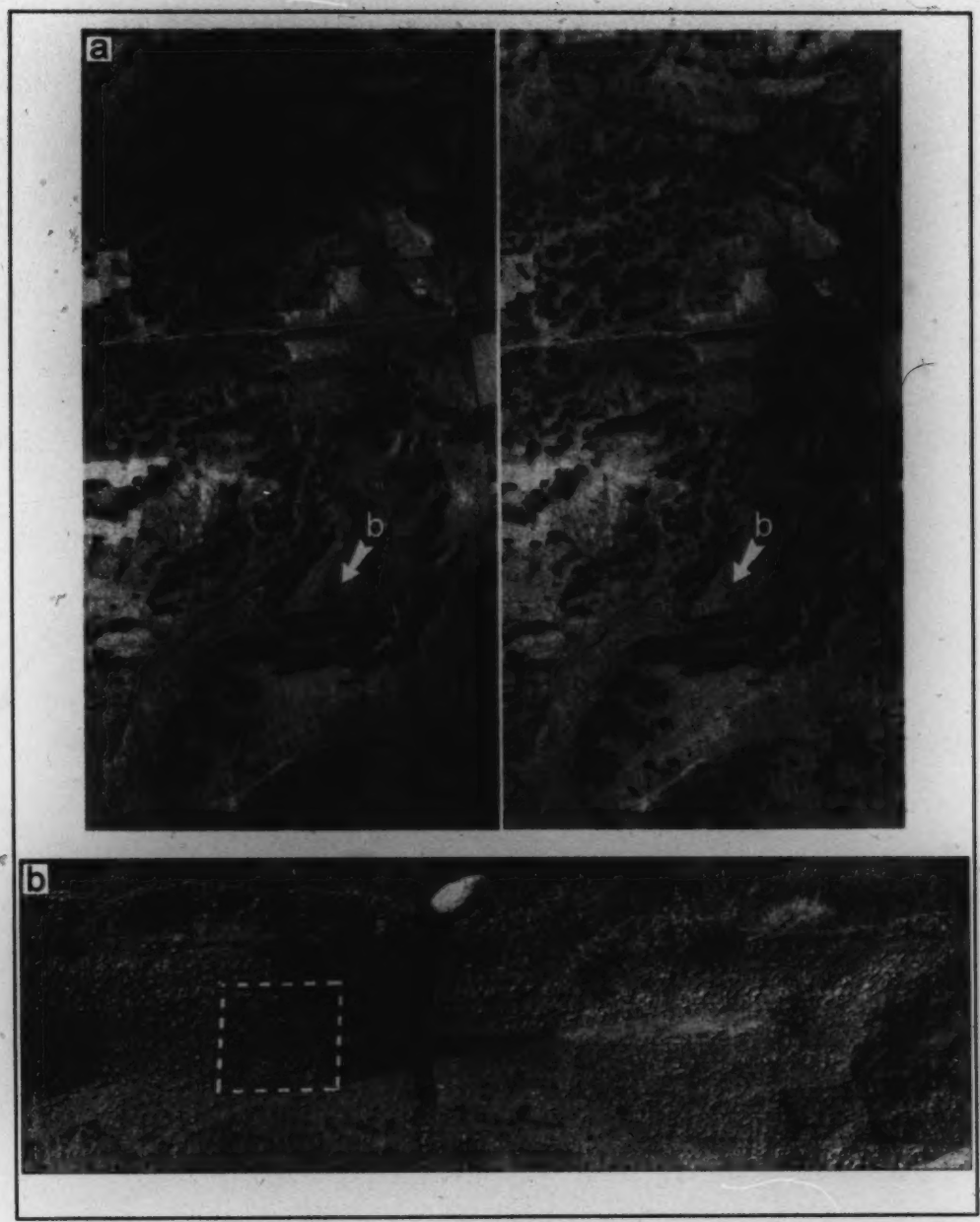

Figure 3.17: Location of an outcrop of preglacial gravels within a glaciofluvial channel, northern part of Zone 3. (a) Stereogram illustrates the large, crescent-shaped residual in the channel. Although slumping of the channel walls has occurred in several places, it does not seem probable that it created the intrachannel residual. (b) Undisturbed preglacial gravel and sand in the intrachannel residual is composed of well-sorted gravels and sands. Note the shield erratic lying on top of the section. The quadrat is 1 m^2 (decimetre divisions).

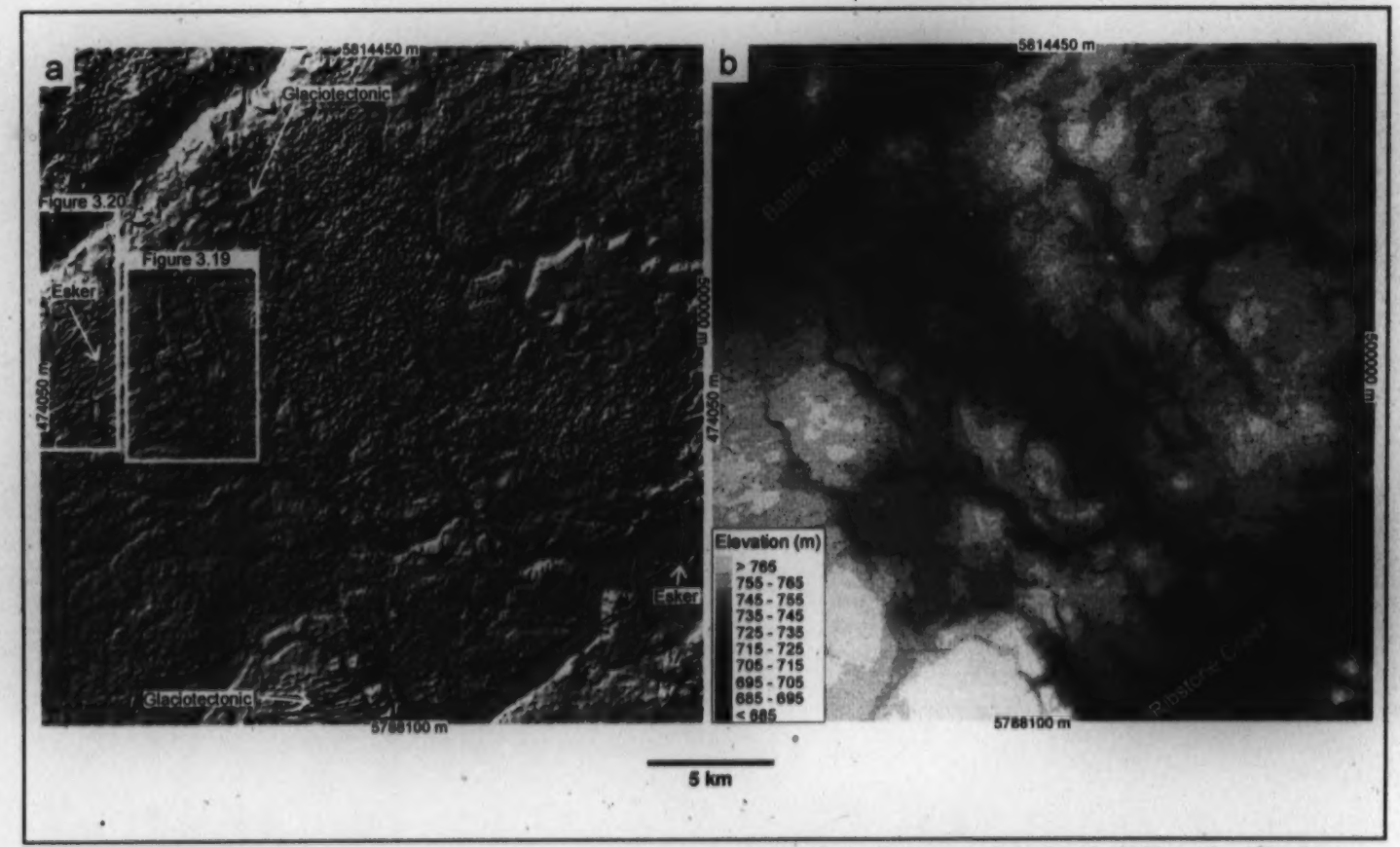

Figure 3.18: Glaciofluvial channels in Zone 3 and location of Figures. (a) Hillshaded relief map (solar azimuth=315°, angle=40°). (b) Classed elevation map. Channels in this zone occupy a broad trough between the Battle River and Ribstone Creek. Channels are often blind-ended. Smaller, linear channels are sometimes perched. Glaciotectonic ridges are usually perpendicular to the channels. Eskers overlie the channels and ridges. Eskers are also observed to be continuous with channel segments.

This saddle is bounded by hummocky terrain to the northeast and ridged terrain to the southwest. Rather than occupying the lowest portions of the trough the best defined channel segments are located on the margins. In this broad, indistinct trough, channels are generally parallel with sinuous sections coincident with northeast-southwest trending ridges (particularly to the southwest).

Channels are poorly interconnected, many are isolated segments. Interconnections are provided by perpendicular, smaller segments or as indistinct linkages where channels meet at low angles. It is common for linking channel segments to be perched or have coincident thalwegs. Several channel segments are blind-ended with indistinct connections. The connections between channel segments are often characterized by hummocky terrain or by broad, flat ground. In some locations small, narrow channels converge on the larger ones, with a depositional fan at the confluence (Figure 3.19). Immediately south of the Battle River several channels are blind-ended with ridged terrain, transverse to the channels, defining their northern limits. Also, the northward extent of one channel is defined by an elongate, relatively flat landform. Undulations, superimposed on this elongate landform suggest that it is likely glaciofluvial.

Channel morphology is highly variable with some segments being relatively sinuous, broad and shallow, while others are straight and narrow (Figure 3.19). Broad, shallow channels are typically lined with lakes which are separated by narrow septa. The paths of these channels often do not conform to the topography, cutting across higher areas. The channels sometimes have convex-up long profiles with numerous undulations because of the hummocky terrain. Though these channels cut across a higher area there is a close relationship between the glaciotectonic ridges and bends in the channel margins. Where higher ridges are present, the channels have diverted around them, utilizing the lower ground between the ridges. Narrow channels have similar relationships with the glaciotectonic ridges, though the topographic control, imparted by the ridges, is more pronounced. It is important to note that many narrow channels in this area do not adhere to the control imparted by the ridged landforms but, rather, they cross-cut them at 90°.

There is an interesting association between glaciofluvial channels, eskers, hummocky terrain, and glaciotectonic ridges. Eskers are found within channels (Figure 3.18), continuous with channels (Figures 3.18 and 3.20), and some cross channels. Eskers are usually perpendicular to the glaciotectonic ridges, though there are some oblique examples. The channels cross-cut the glaciotectonic ridges and also are observed to be defined by them. The esker indicated in Figure 3.18 is continuous with a channel that is incised into the terrain vacated by the glaciotectonically translocated sediment, which in turn is confluent with Ribstone Creek that contains an esker along

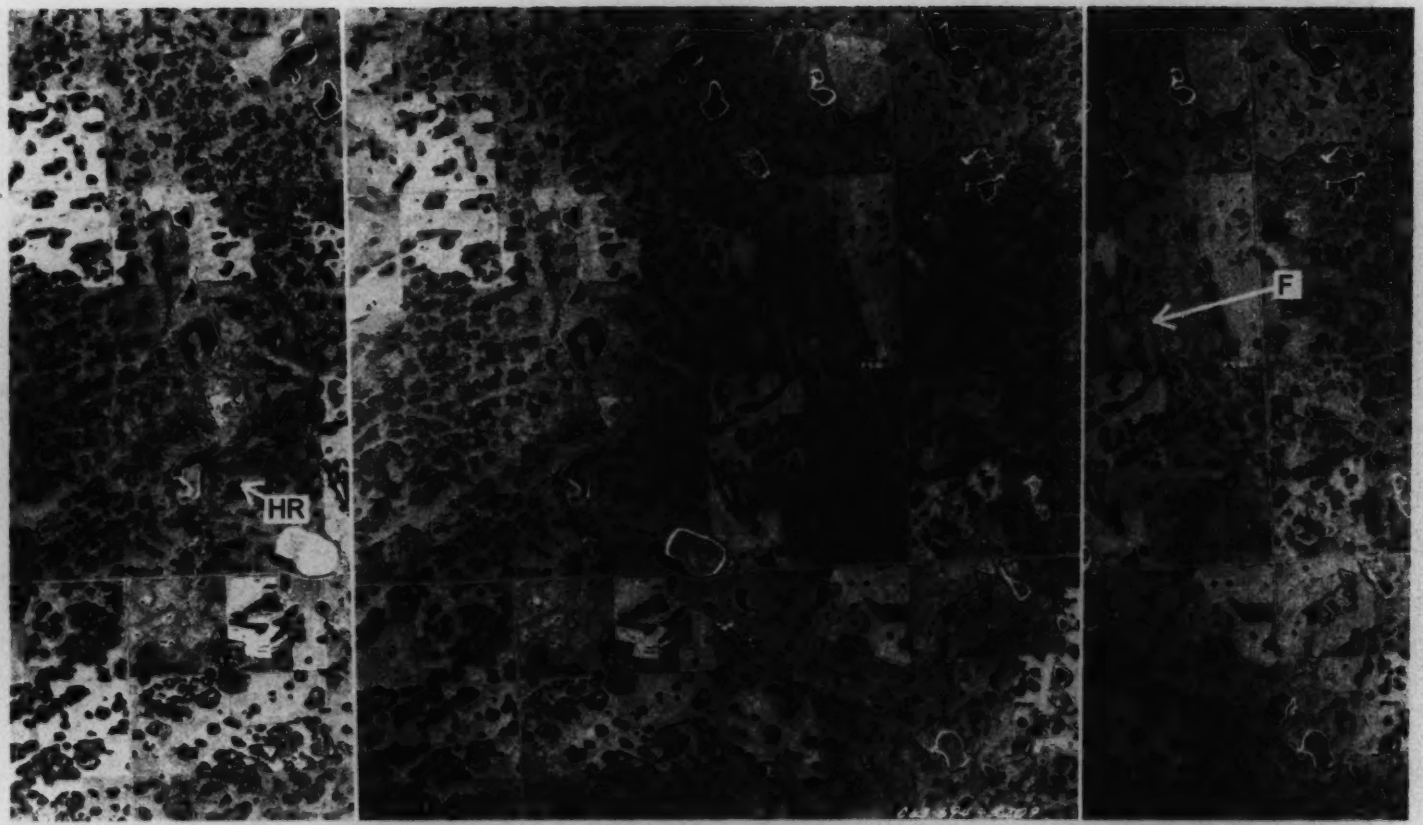

Figure 3.19: Stereogram illustrating the morphology of channels in Zone 4. Channels can either be broad or narrow but are always shallow. Smaller channels are sometimes perched above the larger channels. The relief provided by the glaciotectonic terrain provides some of the control for location and morphology of the channels, though generally channels (and eskers) are oriented perpendicular to the ridges. HR indicates the remnant of a glaciotectonic ridge that has diverted the channel to the west. Occasionally, channels are oriented parallel to the ridges and one empties into a larger channel as a fan (F).

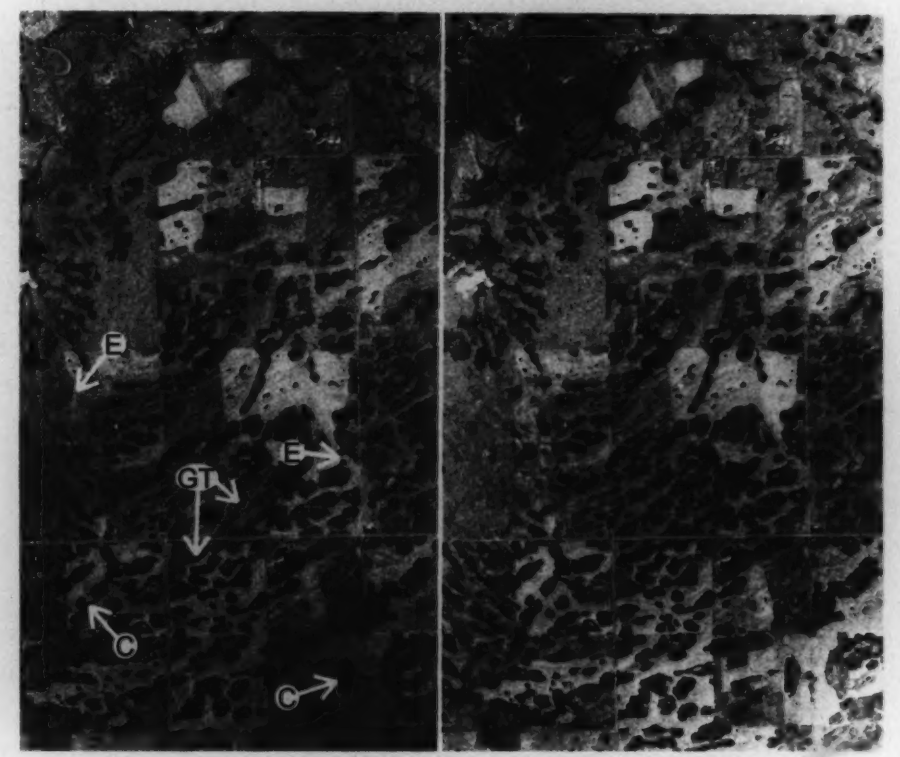

Figure 3.20: Stereogram illustrating the association between eskers (E), channels (C), and glaciotectonic ridges (GT). The two eskers are roughly perpendicular to the orientation of the ridges and superimpose them. The channel appears to be an extension of the esker and is incised into the ridges.

its thalweg. Hummocky terrain is found along the channel bottoms as well as determining the location and morphology of channels. The hummocks are superimposed by the eskers and superimpose the tectonic ridges.

Summary

Surface/subsurface topography and preglacial sediments

Irregularities in the regional and local topography are important factors controlling channel form and location. On a regional scale the topography is gently undulatory, with numerous subtle ridges and saddles. The regional topography gently slopes to the northeast though major departures from this trend occur, especially the Viking upland. Glaciofluvial channel networks have been deflected toward the southeast, around and over major topographic highs, breaching ridges at saddles in the regional landscape (Figures 3.3 and 3.21). Glaciofluvial networks are oriented along the strike of the regional slope, though locally there are major departures from this general trend. On a regional basis glaciofluvial channel networks occupy a wide range of topographic settings and within a parallel or anabranching set of channel segments, many are not at the same elevation. Although there are some connections between the four zones (Figure 3.3), a regional base level, to which channels may have been grading, is not apparent.

At local scales, relief had a profound effect on the location and morphology of channel segments, though it is the apparent contradictions to this control that impart a unique quality to the channel systems. Topographic irregularities on the scale of channels appear to have served as obstacles, rerouting channels, often producing a chaotic sinuosity to segments. Generally, channel segments widen and shallow where they cross depressions and narrow as they cross ridges. Individual channel segments, though affected by the local relief characteristics, do not always reflect this control because several originate in depressions and are traceable over high areas and through the adjacent depressions. Local topography deflects some of the channels but several have undulatory long profiles imposed by the hummocky terrain. However, the overall imprint consists of convex-up long profiles whose relief is much greater than the channel depth. Also, the plan shapes have been partly determined by preexisting ridges, transverse to channel orientation. Ridges have been dissected in several places, producing an anabranched or parallel channel pattern.

Late Cenozoic sediments form a thin, discontinuous mantle over the undulatory bedrock topography. Variations in the thickness of glacial deposits are only partially explained by preferential deposition in bedrock valleys (Figure 3.21). Thick glacial deposits are found on some

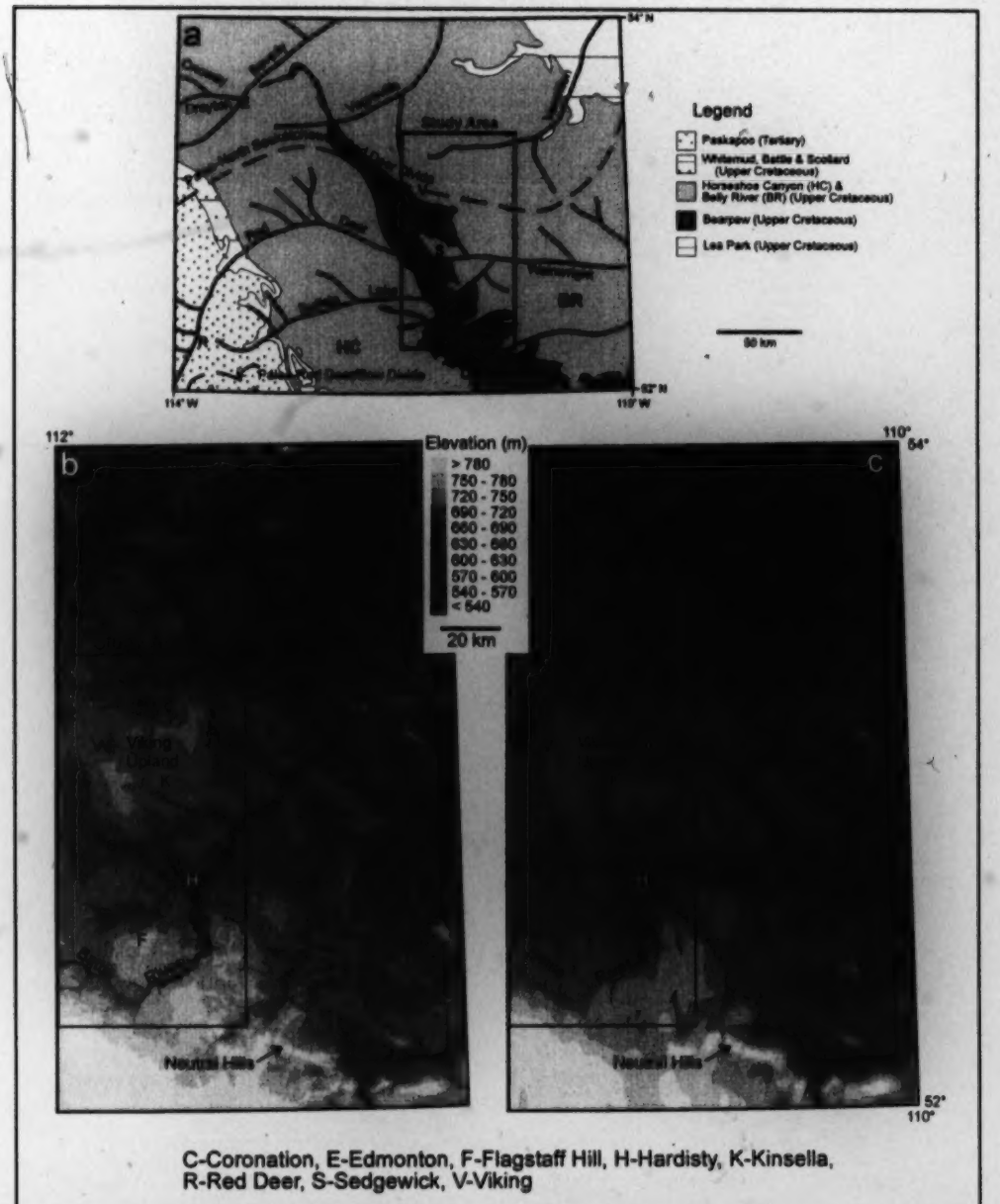

Figure 3.21: Relationship between the surface and bedrock topography in the study area. (a) Bedrock formations and preglacial valleys. Bedrock formations modified from Jackson et al. (1981). Preglacial valleys modified from Pawlowicz and Fenton (1995). (b) Classed elevation map indicating numerous saddles and ridges in the regional topography. (c) Classed elevation map of the bedrock topography. This map shows that most of the ridges and saddles in the surface topography are bedrock controlled.

preglacial highs, on upglacier-dipping slopes, and in preglacial valleys. Saddles in the bedrock topography tended to focus deposition of glacial till and glaciofluvium. Some of the channel systems are coincident with saddles controlled by the bedrock topography whereas others are located on bedrock highs or over tributaries of the Wainwright Valley (Figure 3.21a). The channel systems in the study area are funnelled over preglacial highs and lows, showing a preference for lower areas.

Cretaceous bedrock is locally exposed throughout the study area, and there are large areas over which bedrock is at the surface. The Torlea Flats (Warren 1937) along the western periphery of the study area are largely devoid of glaciogenic sediment. Along the western periphery and swinging from south to southeast, and then east, is a transition zone marked by a break-in-slope from the hummocky terrain on the Viking upland to the Torlea scoured zone. The transition zone curves around the Viking upland near Sedgewick in the form of a continually widening trough separating the upland from the Torlea Flats. In the Sedgewick area this trough contains curvilinear remnant ridges.

The presence of bedrock near or at the surface in these areas is difficult to explain in terms of glacial scouring or non-deposition by the ice sheet. Glaciofluvial channels in the scour zones are typically small and sinuous, conforming closely to the topography. These intermittent channels were cut into the Cretaceous bedrock or thin glaciogenic sediments. Larger channel forms in this scoured zone are concentrated south of Coronation and form scabland topography (Sjogren and Rains 1995). Some larger channels from the Viking upland and south of Sedgewick truncate part of the Torlea scoured zone though channel thalwegs are usually coincident with it. Along the eastern margin of this scoured feature larger channels extending off the Viking upland orthogonally truncate the generally undulatory surface.

The preglacial drainage system indicated in Figure 3.21 contains thick fluvial sediments. These sediments are important because they represented potential aquifers for draining large quantities of glacial meltwater. The location of such deposits in the study area is fairly well known from well logs (Hackbarth 1975) and surface exposures (Figure 3.17). Generally, fluvial sediments have a high hydraulic conductivity that would have enabled subglacial meltwater to be drained efficiently.

Landform Associations

Hummocky terrain is generally found on topographic highs and is rare along the western periphery of the Viking upland. The upland is dominated by hummocky terrain, whereas the only

other extensive tract is on the interfluvebetween the Battle River and Ribstone Creek (Figure 3.3). Hummocky terrain is found only intermittently between these two main areas. In the Kinsella region glaciofluvial channels truncate, and are overlain by, hummocky terrain. This dichotomous relationship suggests a complicated history for formation of the channels and hummocks. Hummocky terrain is closely linked to local elevation changes; for example, the abrupt transition between undulating terrain in low areas to rugged hummocky terrain on adjacent topographic highs. These transition zones are subtle where the elevation change is gradual, and abrupt where local relief is high. This indicates that topography controlled the development of hummocky terrain.

Not all locations characterized by hummocky terrain contain channels. Northeast of Kinsella hummocky terrain is very well developed with classic "knob and kettle" topography. However, there are few channels, even though the elevation of this area is slightly lower than those hummocky areas (with channels) northwest of Kinsella. One channel, located northwest of Kinsella, is discontinuous at either end, starting in hummocky terrain, then crossing a slightly undulatory, shallow basin and ending in higher-elevation hummocky terrain. Thus, topography is only one control on the morphology and location of channels and hummocky terrain. In the southeast corner of the study area, hummocks are located on slightly higher ground flanking the channelized area. At this location hummocky terrain has a distinct trend as the hummocks and hollows are associated with large northeast to southwest trending ridges. In this area, one well-developed channel crosses the hummocky zone and appears to have been diverted by the large ridges.

Glaciofluvial channels within hummocky zones are usually smaller than those not associated with hummocks. Southeast of Sedgewick, hummocky terrain is situated on an interchannel residual, and is accompanied by poorly-developed hummocky terrain on adjacent residuals. Channels outside hummocky terrain, are commonly flat floored and contain saline lakes, indicating that bedrock is at or very close to the surface. Saline lakes are absent where channels are incised into sediment filling preglacial valleys.

There are only a few examples of large-scale flutings/remnant ridges in the study area, the most prominent of which are located near Sedgewick. They are slightly arcuate, curving to the northeast, with wavelengths of ~200 m, amplitudes of ~3-5 m and lengths up to ~8 km. Such linear features are located in the eastern part of the Torlea scoured zone as it sweeps around the southern margin of the Viking upland. Although there are many examples of fluting/remnant ridge landforms in the regional scoured zone (Torlea Flats), there are few within the study area. The fluting is truncated by glaciofluvial channels.

Glaciotectonic landforms are throughout the study area range from large hills composed of thrust sheets of Cretaceous bedrock, such as the Neutral Hills and Flagstaff Hill (Figures 3.2 and 3.3), to much smaller arcuate and linear forms found on intrachannel residuals. Glaciotectonic ridges are also located in the transition zones between the hummocky and scoured zones. Andriashek and Fenton (1989) emphasized the importance of glaciotectonics in producing morainal landforms in Alberta. Linear or slightly arcuate glaciotectonic ridges are presumed to trend perpendicular to ice sheet flow (Kupsch 1962). In cases where the glaciotectonic landforms have much greater relief than the adjacent channels, the channels deflect around them (e.g., channels on the east flank of Flagstaff Hill, Figure 3.13). By contrast, relatively subtle ridges are dissected by channels, though the channel forms and paths indicate that the ridges exerted some control on their formation (Figures 3.4 and 3.15). In this setting, channels often constrict as a ridge is crossed and widen across the depression. This widening is primarily caused by postglacial gullying, because the depressions are obvious foci for enhanced erosion. Glaciotectonic ridges exert the same control on the location and morphology of channels as preglacial topographic elements.

Rare eskers are uncommon in the study area, are critical for inferring the sequence of landscape evolution. Several sinuous ridges which resemble eskers are mélanges of diamicton and contorted gravels. These landforms were interpreted by Stalker (1960) as being casts of Röthlisberger channels, whereby the subglacial tunnel was filled by pressing as drainage increased the effective pressure of the ice sheet. Thus, caution must be exercised when interpreting similar landforms strictly on the basis of morphology. Several true eskers are closely associated with the glaciofluvial channels and hummocky terrain. They cross channels or follow them. In all instances esker sediment lies stratigraphically above other glaciogenic sediments. The landforms either lie within troughs incised into, or are superimposed on, hummocky terrain. Figure 3.12 shows an esker passing from channel and over the adjacent interfluve. It is important to note that, whereas, the channel crosses the interfluves, which are approximately 5-7 m high, the esker ridge is only 3-4 m high. Other eskers found in the study area are aligned parallel, or slightly oblique, to the orientation of the channels. These eskers lie entirely within the channels and are often associated with sorted sediment.

Discussion

The glaciofluvial channels described in this paper have varied topographic settings, morphologies, and sediment/landform associations. Thus, a single, universal genetic explanation is unlikely. The size and topographic setting of these channels rule out their genesis by postglacial subaerial incision. Nevertheless, there are several possible glacial paleoenvironments that they might represent: ice-marginal channels, spillway channels, 'stream trenches', and subglacial tunnel channels/valleys.

Several characteristics of the glaciofluvial channels in the study area are not consistent with an ice-marginal or sub-marginal origin. First, many of the channels (in individual zones) are integrated. Generally, ice-marginal (lateral) channels are confined by ice and topography and occur as nested segments (Dyke 1993). Second, ice-marginal channels form time-transgressively with downwasting; older channels are abandoned for lower, younger ones (Beaty 1975). Such ice-marginal channels are common where glacier ice was cold-based (*cf.*, Benn and Evans 1998), though Dyke (1993) suggested that they also formed along the margins of temperate glaciers, such as the southwest sector of the Laurentide ice sheet. Although some of the channels in the area were undoubtedly used ice-marginally during ice sheet retreat, the topographic setting of the channels does not support the initial erosion of the channels as ice-marginal. Third, and most important, convex-up and undulatory thalwegs, present in many parts of the study area, require that the water that carved the channels be under hydraulic pressure during their formation.

Spillways or proglacial drainage channels were not important in the formation of these channels. First, the morphologic sequence described by Kehew and Lord (1986) is not seen anywhere in the study area. Second, spillways were formed by catastropic releases of meltwater from one lake basin to another, but no large basins are present. There must have been some ponding of meltwater, but there are no obvious basins that could have supplied the amount of water necessary to carve the large meltwater channels. Third, where spillways enter receiving basins, the geomorphology is characterized by large fans and/or deltas (Lord 1991; Smith and Fisher 1993). Small alluvial fans are present in the Battle River valley but there are no large fans, with the possible exception of the Hardisty basin, associated with the glaciofluvial channels.

Another possibility is that the glaciofluvial channels might have formed in 'stream trenches' as suggested by Gravenor and Bayrock (1956). Their conclusion was based on field observations in parts of Zones 1 and 2 (Figure 3.3). This interpretation relies on the juxtaposition of hummocky terrain and the channels (Figure 3.22). 'Stream trenches' interpreted as ice-walled channels formed

during widespread stagnation (Gravenor and Bayrock 1956; Gravenor and Kupsch 1959; Parizek 1969). Although Gravenor and Bayrock (1956) and Gravenor and Kupsch (1959) hinted at the possibility of subglacial or conduit flows, they referred to the trenches as ice-walled channels because some were 1 km wide. Yet the fact that some are so wide makes it highly unlikely that the hummocky terrain on channels floors could be slumped glacial sediment. The preexistence of channels was suggested by Gravenor and Ellwood (1957) as a possible explanation for some channels, particularly those that are underlain by sorted sediments. The absence of plunge pools and the gradual transitions between channels and hummocky terrain support the hypothesis of Gravenor and Bayrock (1956) that these channels were filled in by morainal material.

This hypothesis was appended by others (e.g., Parizek 1969) and has merit. There are two important drawbacks. First, the 'stream trenches' must have initially formed subglacially under pressure because they have convex-up long profiles. It is thus impossible to attribute the channels in Zones 1 and 2 to subaerial erosion from supraglacial lake drainage. Second, in several locations along the 'stream trenches' there are hummocks that are composed of bedrock. Bedrock hummocks, interspersed with diamicton hummocks, indicate that much of the intrachannel morphology is erosional. The bedrock hummocks and the wide channels indicate that slumping is a highly unlikely primary cause of the intrachannel relief.

In Zone 3, channel morphology is markedly different from channels in Zones 1 and 2. Bayrock (1957a, b) mapped the large channels in Zone 3 as stream trenches/spillway channels primarily on their association with hummocky terrain. As previously mentioned, the channels cannot be spillway channels, either on the basis of morphology (Kehew 1982), or their undulating long profiles. Also, the anabranching pattern and lack of source basins makes this interpretation tenuous. Channels in Zone 4 are very similar to those in Zones 1 and 2, and to others in Alberta and Saskatchewan (Parizek 1969; Evans and Campbell 1995). The topographic setting of these channels, as with others further north, indicates a subglacial formation. The presence of at least one fan within a larger channel indicates deposition following channel erosion.

Although eskers are not widespread, the relative timing of the formation of eskers and glaciofluvial channels is critical to inferring their paleoenvironments. Eskers are found along the floors of channels, crossing channels/interfluves at right angles, and also may be continuations of channels. The esker indicated in Figure 3.12 crosses a channel and the adjacent interfluve at nearly right angles. This juxtaposition indicates a significant reorganization of the glacial hydrologic system between formation of the glaciofluvial landforms. Eskers have been interpreted as segmental

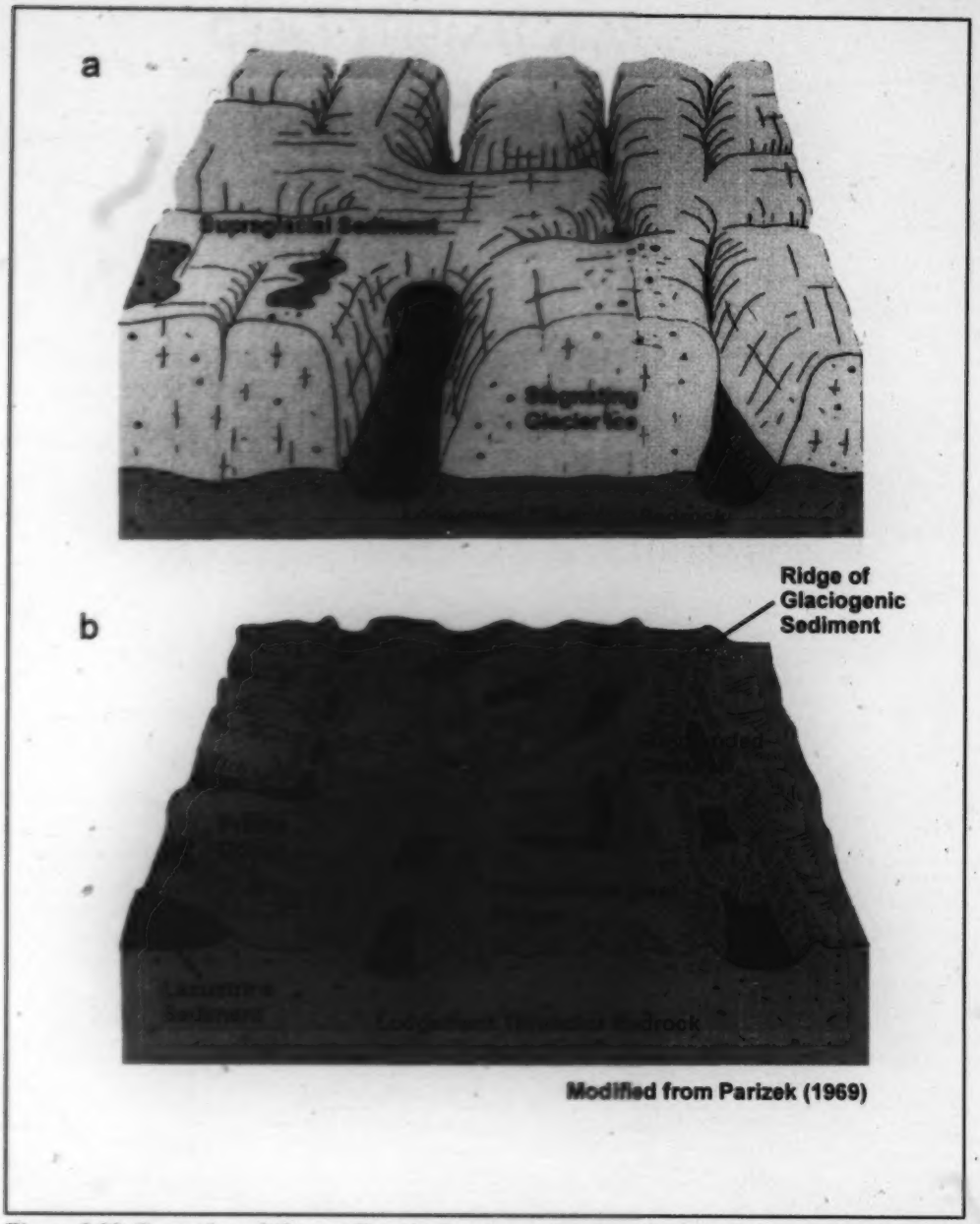

Figure 3.22: Formation of "Stream Trenches" and associated landforms as interpreted by Gravenor and Bayrock (1956) and Parizek (1969). (a) These channels were interpreted to have formed in crevasses in stagnant ice. (b) The hummocky terrain on the channel floors was thought to be the result of glaciogenic sediment slumping into the channels. Ridges formed along the margins of the channels were attributed to squeezing-up of sediment into the channels and/or supraglacial letdown.

or continuous ridges of glaciofluvial sediment. Hebrand and Åmark (1989) envisaged eskers as ice-marginal landforms that terminated in fans. However, Brennand (1994) suggested that eskers were formed continuously along a conduit which may have undulatory long profiles. Because marginal fans are absent in the study area, it is likely that the eskers were formed in continuous conduits and that the undulatory long profiles were formed by hydraulically pressure. Eskers in Zone 4 are continuous with glaciofluvial channels. This relationship requires that both were formed subglacially.

Many studies have focussed on glaciotectonics and their glaciodynamic implications (eg., Aber et al. 1989), and several have been conducted in Alberta (eg., Kupsch 1962; Stalker 1976; Moran et al. 1980; Tsui et al. 1989; Campbell and Evans 1990). Most models for glaciotectonism indicate that displacement of preglacial sediments (including bedrock) and glaciogenic sediments occurred ice-marginally. Permafrost (Attig et al. 1989) and/or high subglacial water pressures (Bluemle and Clayton 1984) are commonly invoked in explanations of glacial tectonics. The presence of glaciotectonic terrain is important in the interpretation of the glaciofluvial channels in the study area. First, at nearly all the locations where channels and glaciotectonic terrain are found together, the channels truncate the glaciotectonic ridges. Second, the channels commonly have convex-up or undulatory long profiles which have been partly controlled by the presence of the ridges. Third, eskers overlie the ridges and are continuous with some of the channels. These relationships require that the glaciotectonic ridges were formed prior to the channels and the eskers, which are certainly subglacial. This necessitates that the glaciotectonic ridges were formed proglacially (during advance) or subglacially, prior to the erosion of the main glaciofluvial channels.

The importance of subglacial aquifers in the formation of glaciotectonic terrain and subglacial, glaciofluvial landforms is a critical consideration for interpreting landform formation sequences. The glaciohydrologic significance of buried fluvial sediments in Europe has been investigated by Boulton et al. (1995) and Piotrowski (1997). Boulton et al. (1995) argued that high hydraulic conductivities in subglacial sediments could transmit all subglacially derived meltwater to proglacial areas. Conversely, Piotrowski (1997) showed that subglacial sediments were able to transmit only about 25% of the meltwater. The remainder was likely ponded subglacially and then catastrophically released. Arguing from the absence of sheetflood landforms, he inferred that the meltwater was released in tunnel valleys. The fact that glaciofluvial channels are present in areas underlain by unconsolidated sediment sequences indicates that either the meltwater drainage occurred more rapidly than the aquifer could accommodate it or that the sediments were frozen at

the time of channel cutting. If steady state erosion of these channels occurred, meltwater would be expected to have drained though the highly permeable preglacial sediment.

Subglacial glaciofluvial landforms have received considerable attention in the literature over the last few decades. The most spectacular of these landforms are tunnel valleys/channels. Several models for the formation of tunnel valleys have been proposed, each with their own strengths and weaknesses. The model of tunnel valley formation proposed by Boulton and Hindmarsh (1987) does not take into account that: (1) many tunnel valleys/channels have been eroded into undeformed bedrock that presumably would not deform, (2) lateral constraints of sediment deformation caused by limited till thickness and yield strength would limit the size of a valley created in such a way (Alley 1992), and (3) Walder and Fowler (1994) showed that steady state drainage over a deformable bed would occur as uniformly distributed, shallow canals, not as arborescent R-channels. The application of the segmental tunnel valley/channel models of Wingfield (1990) and Mooers (1989) also has some drawbacks. The segmental formation of tunnel valleys/channels requires that they are remnants of plunge pool erosion (Wingfield 1990). The segmental formation envisaged by Mooers (1989) does enable water to be under hydraulic pressure which is critical for formation of uphill channel paths. Yet the models presented by Wingfield (1990) or Mooers (1989) cannot account for the channel continuity or integration present in the study area. Therefore, not one theory of tunnel valley/channel formation indicated above adequately explains the different morphologies present in the study area.

Interpreting all channel segments as products of glacial/deglacial processes is probably incorrect due to the likelihood of reoccupation of preglacial drainage systems by glacial meltwater. The possibility that some channel segments, expressed in the present topography, were initiated preglacially as tributaries to the paleodrainage raises uncertainty about the antiquity of channel formation (Booth and Hallet 1993). Small paleotributaries would have been eroded by the overriding ice sheet, then mantled by glacial sediment and, subsequently, provided depressions that focused the erosion of channels. One example of a preexisting channel is shown in Figure 3.9b.

The glaciofluvial channels in the study area are predominantly subglacial landforms. The nature of their formation is closely tied to the preglacial topography, the subglacial topography, and glacial sediments/landforms. The relationship between the glaciotectonic ridges, hummocky terrain, eskers, and the channels, indicates that they were formed under hydraulic pressure, far from the glacier margin. The size, and predominantly erosional nature of the channels indicates that large quantities of water were released catastrophically. The connections between the four zones indicate

that they shared the primary water source(s), though site-specific topographic and sediment characteristics created the variety of morphologic expressions present in the study area.

Conclusions

The landform/sediment associations in the study area indicate that the glaciofluvial channels are subglacial landforms. Also, the large size and interconnected nature of most channels indicate catastrophic drainage rather than steady state conditions. Many of the relationships observed for the channels in this area are consistent with the waning stages of a large-scale subglacial meltwater drainage event. On the western periphery of the study area, a relatively flat plain, referred to as the Torlea Flats (Warren 1937), delineates one edge of the Viking 'moraine'. This plain has been featured prominently in Rains et al. (1993) as evidence for large-scale subglacial flooding. Chapter Two investigated the large-scale morphology within this plain and concluded that there were several diversions from this main floodpath.

The regional landform associations and site-specific characteristics of the glaciofluvial channels indicate the following sequence of landform formation:

1. The preglacial topography, characterized by well-developed fluvial systems, was modified by the encroaching Laurentide ice sheet. At this time ice-marginal channels were eroded, partly occupying preexisting tributaries.

2. The combination of ice-marginal glaciotectonics, and glacial deposition modified the preglacial fluvial landscape, muting some of the existing relief. The emplacement of till and translocation of preglacial sediments provided additional topographic elements to the subglacial environment.

3. A large subglacial drainage event eroded the Torlea Flats and overtopped the Viking upland where turbulent flow structures enhanced the subglacial topographic elements. The subglacial topography was modified by this turbulent flow, truncating banding in the till and bedrock creating erosional hummocky terrain (*cf.*, Munro and Shaw 1997). The flow structures responsible for this modification were similar to kolks that have been implicated in forming potholes in the Channeled Scabland, Washington State (Baker 1978b).

4. Rapidly, the sheetflow began to channelize, concentrating the erosion into nearly parallel threads that passed through the depressions and over the highs in the subglacial topography. These threads of enhanced erosion (incipient tunnel channels) were deflected by some elements of the hummocky terrain but generally were oriented parallel to the main flood tract in the Torlea Flats. As this catastrophic release of meltwater continued, increased shear stress adjacent to the flood paths caused glaciotectonic displacement of bedrock and glaciogenic sediment. This glaciotectonism occurred on the highest points of the landscape (e.g., northeast of Bellshill Lake).

5. As the sweeping diversion of the eastern flood path that passed through Sedgewick became established, water was forced southward in channels east of Flagstaff Hill. Hummocks in the preexisting depression (southeast corner of Zone 3) were eroded by the flow, leaving boulder lags and significant glaciofluvial deposits. Part of the meltwater flow that was diverted through this area was likely funnelled into what now is the Battle River valley.

6. As the discharge dropped, the Sedgewick diversion was abandoned though flow through the Birch Lake depression continued for a short time, connecting to the Kinsella basin and southward to the Hardisty basin, thereby partly truncating the landforms in the Sedgewick area.

7. After the main flow from the subglacial flood ceased, minor subglacial, and later ice-marginal meltwater used some of the channels that were earlier eroded by this waning subglacial flood. Slumping of glacial sediments into the channels partly produced the hummocky floors in the channels, but most of the relief was the result of enhanced erosion of threads of turbulent meltwater with near-vertical vortices (kolks).

8. After cessation of the subglacial flood(s) eskers were deposited in conduits that only partly mimicked some of the meltwater channels. Because some eskers are perpendicular to the channels it is reasonable to conclude that the glaciohydrologic system had been reorganized to a large extent, possibly to conform to the topography of the ice sheet. This reorganization occurred much later than the formation of the channels.

This interpretation of the northern Viking 'moraine' has important implications for regional studies of Quaternary paleoenvironments. First, if the hummocky terrain and related landforms are predominately subglacial landforms then using the 'moraine' as an ice-marginal indicator for deglacial reconstructions is inappropriate. Second, given the connections with the Battle River valley, what does this mean in terms of when it was incised; preglacially, subglacially as a tunnel valley, or as a spillway from the Glacial Lake Edmonton basin (Bayrock 1957b)? Third, what was the destination for most of the meltwater that passed through the area in these tunnel channels?

Formation of the tunnel channels described herein is consistent with the regional interpretation presented in Chapter One. It is important to determine if the site-specific sedimentologic/morphologic characteristics of hummocky terrain and glaciofluvial deposits support this interpretion. Further, do these incipient tunnel channels represent the transition between a channelizing sheetflow into a stable canal system (Walder and Fowler 1994) that was frozen in time when the water source was rapidly cut off?

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CHAPTER FOUR: THE KINSELLA GLACIOFLUVIAL COMPLEX: AN ARGUMENT FOR SUBGLACIAL CAVITY FILL.

Introduction

Massive volumes of meltwater were associated with the large Pleistocene ice sheets. The nature and environment of meltwater evacuation from these ice sheets created a myriad of erosional and depositional landforms. Glaciofluvial landforms and sediments were formed in proglacial environments as outwash, largely controlled by the diurnal and seasonal variations in meltwater, or as the result of catastrophic releases of meltwater stored in proglacial and subglacial lakes. Catastrophic draining of proglacial lakes, along the southern periphery of the Laurentide and Cordilleran ice sheets, has been the subject of significant research (e.g., Bretz 1969; Baker and Nummedal 1978; Kehew and Lord 1986; Teller 1990; Teller and Kehew 1994). The erosional products of these catastrophic releases of meltwater are commonly spectacular and may be predictable in character (Kehew and Lord 1986). Because of the variety of settings, sedimentation associated with these floods was highly variable both in spatial extent and depositional style. Deposits often formed bars of eddy, expansion, and pendant types where the deposits were emplaced on land (Baker 1978; Sjogren and Rains 1995) or deltas/fans where they were deposited into lakes (Lord and Kehew 1987; Smith and Fisher 1993).

Glaciofluvial sedimentation in subglacial environments is also well documented, including many studies on the morphology and sedimentology of eskers (e.g., Hebrand and Åmark 1989; Brennand 1994; Warren and Ashley 1994), and tunnel valleys/channels (e.g., Brennand and Shaw 1994; Piotrowski 1994; Sjogren and Shaw 1996). Sedimentation in eskers and tunnel channels/valleys occurred in both subglacial and ice-marginal locations. Connections between subglacial eskers and tunnel channels/valleys and ice-marginal environments are often inferred by the presence of fans (Hebrand and Åmark 1989; Patterson 1994). Although sedimentation in subglacial lakes is seldom reported, McCabe and O'Cofaigh (1994) stressed the importance of connections between subglacial glaciofluvial and subglacial lacustrine environments.

It can be drawn from these studies that depositional styles were site-specific. Sedimentary characteristics which might be used to differentiate subaerial and subglacial glaciofluvial sedimentation, are often elusive; the nature of the sediments must be considered in both topographic and sedimentologic contexts before reasonable interpretation may be achieved.

Problem Statement

Glaciofluvial landforms including eskers, subglacial channels, and spillways are common in the southwest sector of the former Laurentide ice sheet. Extensive glaciofluvial sediments are not common throughout the Viking district (Figure 4.1a), but are concentrated in a system of channels in the Kinsella area. The extensive glaciofluvial system is named, herein, the Kinsella Glaciofluvial Complex (KGC). Sediments of the KGC are highly variable in texture and architectural style, indicating large variations in competence, routing, and sediment availability. The primary objective of this paper is to interpret (on the basis of the sedimentary architecture, landform associations, and topographic setting) the paleoenvironments in which these sediments were deposited. Two generalized paleoenvironments were probably connected to this problem; subglacial and/or proglacial. The KGC was interpreted as outwash, associated with stagnating ice, by Gravenor and Bayrock (1956) which was echoed by Gravenor and Ellwood (1957) and Bayrock (1958). Another possibility is that the KGC was formed subglacially, in a cavity or subglacial lacustrine setting (Sjogren 1998). Detailed analysis of the sediments contained in the massive glaciofluvial complex, its connectivity with adjacent glaciofluvial landforms, and associated landforms should elucidate the dominant paleoenvironment(s).

Study Area

Previous work on the Viking 'moraine'

The KGC is part of an extensive system of hummocky terrain, channels, and glaciotectonized terrain collectively referred to as the Viking 'Moraine' (Warren 1937). He proposed that the Viking 'Moraine' represented a terminal glacial position, prior to the late Wisconsinan glaciation. This was prompted by the tentative conclusion that the 'moraine' along the Missouri Coteau represented the late Wisconsinan glacial maximum (Johnston and Wickenden 1931). Bretz (1943) conducted the first detailed study of glacial meltwater channels in Alberta and Saskatchewan, and noted that the Viking 'Moraine' failed to conform to the map of Warren (1937). Bayrock (1955) hypothesized that the Viking and Coteau 'Moraines' were recessional moraines formed during the late Wisconsinan glaciation. Christiansen (1979) interpreted part of the Viking 'Moraine' as a recessional late Wisconsinan feature and stressed that meltwater channels were critical to reconstructing deglacial chronologies. Klassen (1989) echoed this idea and stated that hummocky 'moraines' were locations of glacial sedimentation for multiple glaciations. At present, it is commonly accepted that only the late Wisconsinan Laurentide glaciation occurred in this area

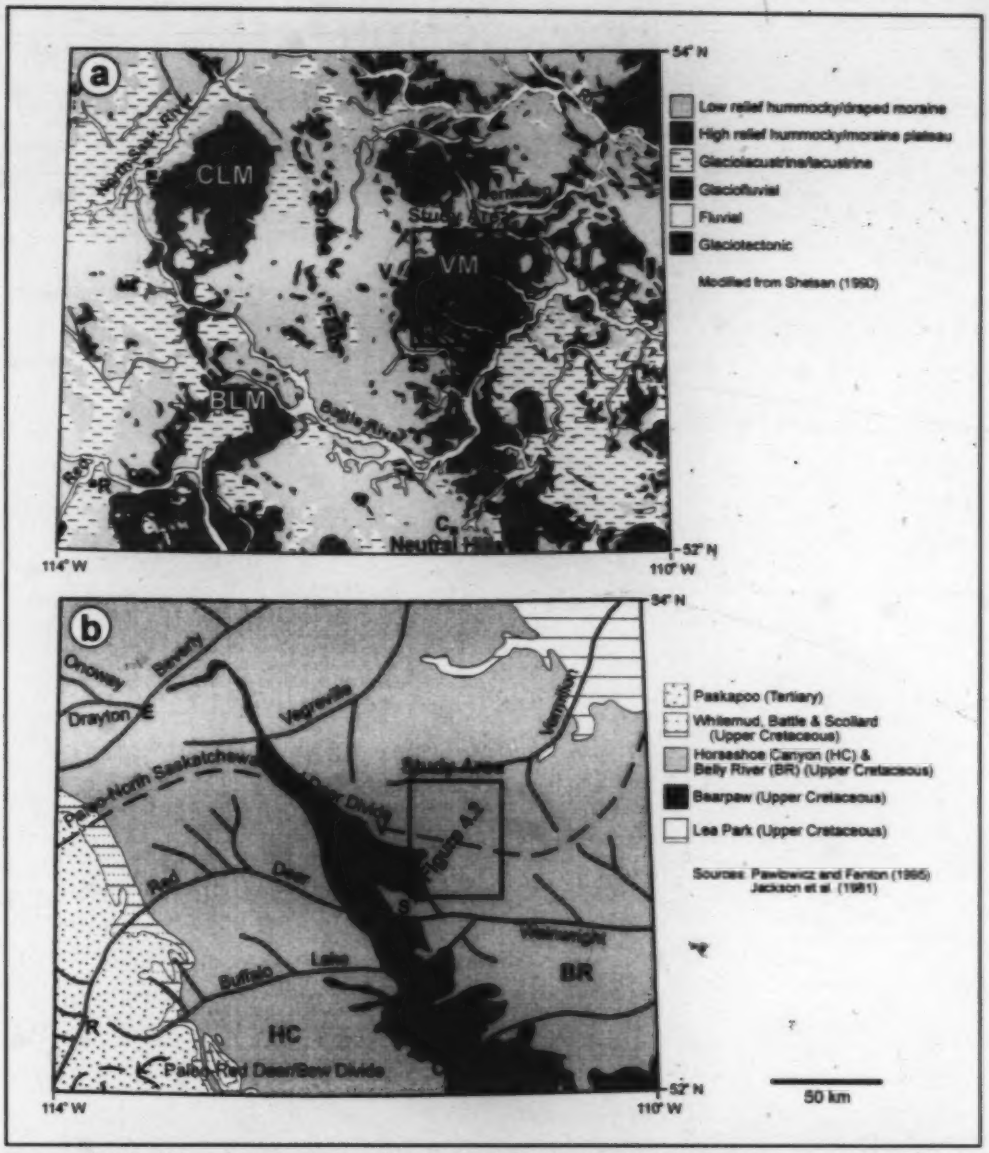

Figure 4.1: Setting of the study area in east-central Alberta. (a) The study area was located on a large, bulbous portion of the Viking Moraine (VM), near the present drainage divide between the Vermilion and Battle Rivers. This part of the VM was dominated by hummocky terrain with one major trough that is oriented N-S that deflected to the SE at the Kinsella Glaciofluvial Complex (KGC). This elevated area is referred to as the Viking upland. (b) Generalized bedrock formations and the location of preglacial valleys and drainage divides. The study area was located on the preglacial divide between the ancestral Vermilion and Wainwright valleys. C-Coronation, E-Edmonton, K-Kinsella, KGC-Kinsella Glaciofluvial Complex, R-Red Deer, S-Sedgewick, V-Viking, CLM-Cooking Lake moraine, BLM-Buffalo Lake moraine.

(Liverman et al. 1989; Young et al. 1994; Young 1996). Rains et al. (1993), Shaw et al. (1996), Munro and Shaw (1997), Munro-Stasiuk and Sjogren (1998), and Sjogren et al. (in review) contradicted previous assertions that 'morainal' zones were recessional features and suggested that 'morainal' zones in central and southern Alberta were the products of subglacial fluvial erosion of preexisting sediment, rather than resulting from ice stagnation (Gravenor and Kupsch 1959).

Landform/Sediment Associations

The Viking upland (roughly defined by the 700 m contour, Figure 4.2) is dominated by hummocky terrain with 5-10 m of local relief, punctuated by glaciofluvial channels and the KGC. These glaciofluvial channels were interpreted as 'stream trenches' by Gravenor and Bayrock (1956). 'Stream trenches' were thought to have been formed in crevassed, stagnating glacier ice. The hummocky channel floors were attributed to slumping of material into the ice-walled channels. This interpretation was modified by Bayrock (1958) because many of the channels are about 1 km wide. The morphology of these channels formed a continuum from aligned potholes to scarp forms that appeared largely dependent on the thickness of glacial sediment overlying the bedrock. Many have pronounced convex-up long profiles and contain glaciofluvial sediment and/or glacial till (Chapter Three). Small eskers were found within some channels and are dispersed throughout the hummocky terrain, although they are not pervasive. Eskers are found along the thalwegs and also at nearly right angles to the channels. Either setting places the formation of the 'stream trenches' **before** the eskers developed.

Bedrock is near the surface at many locations in the study area; exposed in 'stream trenches', hummocky terrain, glaciotectonic terrain, and large scoured areas west of the study area (Sjogren et al. in review). Glaciotectonic terrain, is expressed as arcuate hills (imbricate slabs) of Cretaceous bedrock (*cf.*, Kupsch 1962; Tsui et al. 1989; Campbell and Evans 1990). In the immediate vicinity of the KGC, no large systems of glaciotectonic landforms occur (Figure 4.1a), although there is widespread evidence of smaller-scale glaciotectonic deformation in sediments within hummocky terrain. Bedrock is also exposed in hummocks found within 'stream trenches' and occasionally in hummocks located on higher ground. Bedrock is extensively exposed at the surface to the west in the Torlea Flats (Warren 1937). The Torlea Flats form a gently rolling plain whose subtle topographic expression reflects the underlying bedrock that is intermittently mantled by a thin veneer of glaciogenic sediment. The paucity of glaciogenic sediment in this area has been attributed to prolonged interglacial erosion (Warren 1937), enhanced sliding/non deposition (Gravenor and

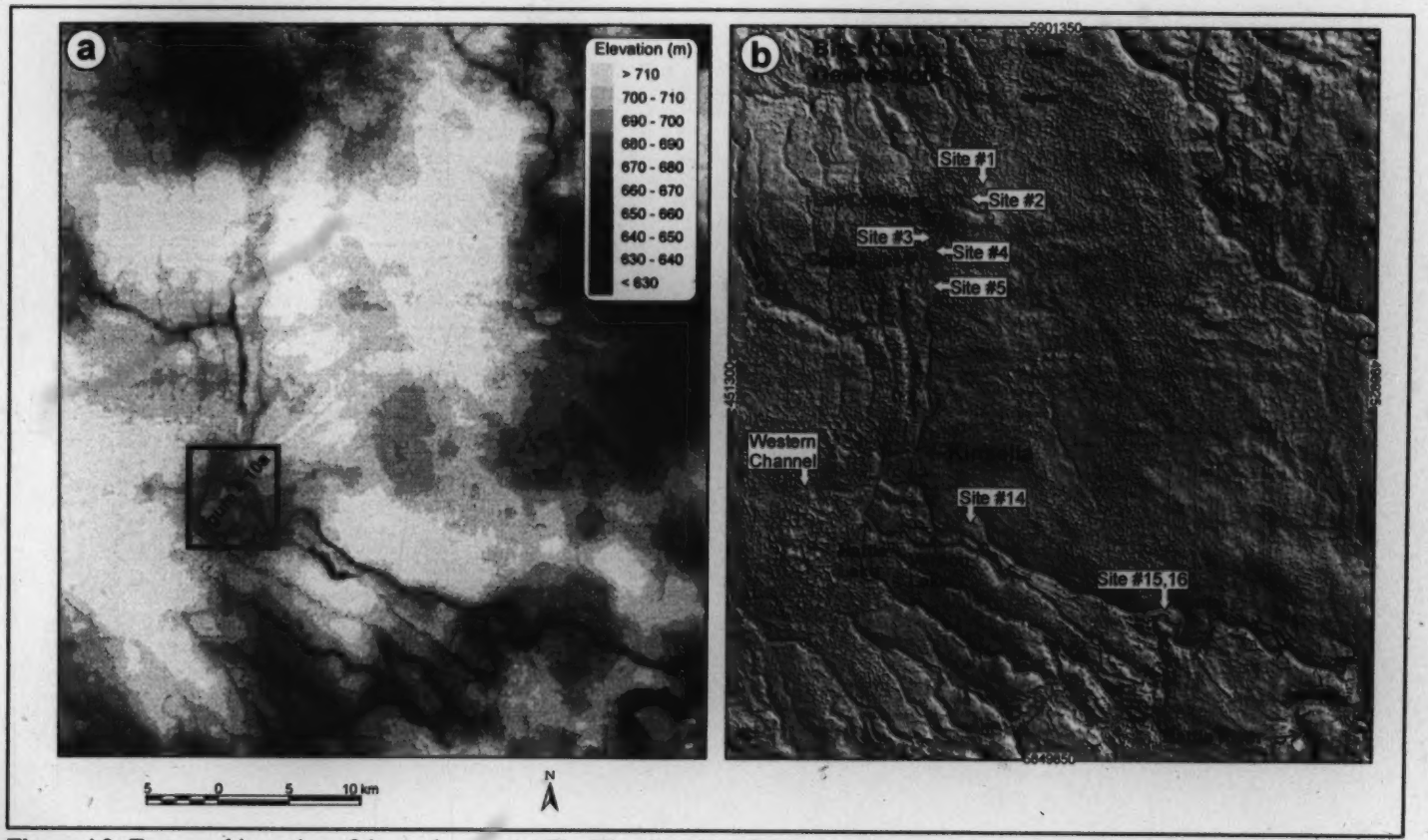

Figure 4.2: Topographic setting of the study area. (a) The Kinsella Glaciofluvial Complex (KGC) is indicated by the box. The Viking upland is roughly defined by the 700 m contour. (b) Hillshade model of the area. Simulated solar azimuth/angle = 45/40. The margins of the figure are given in UTM coordinates. In both figures, note the trough that extends from the Birch Lake depression, through Lac Loranger, and deflects slightly eastward. This trough is accompanied by several shallow depressions in the Viking upland. This trough is paralleled by erosional channels to the north and obliquely cross-cut by channels that deflect toward the Battle River in the south.

Bayrock 1955), or widespread subglacial fluvial erosion (Rains et al. 1993; Shaw et al. 1996).

The bedrock topography and distribution of preglacial sediments are critical to understanding the distribution of glacial and glaciofluvial landforms in this area. The main thalwegs of preglacial river systems have been compiled/updated by Pawlowicz and Fenton (1995). The study area is situated on the drainage divide between the ancestral North Saskatchewan and Red Deer river systems (Figure 4.1b). Hackbarth (1975) investigated the Wainwright valley (situated immediately south of the study area) and showed that the valley is up to 150 m deep and dominated by gravels and sands near the thalweg. In Chapter Three, I indicated that preglacial gravels, likely related to a tributary of the Wainwright valley, were exposed in erosional channels. The arrangement of preglacial valleys has been important in deciphering the possibility of multiple glaciations in the area. Andriashek and Fenton (1989) reported multiple till/fluvial sequences in buried valleys to the north. Previously, Bayrock (1955) stated that there was no evidence for multiple glaciations in the study area. Young et al. (1994) and Young (1996) reported extensive biostratigraphic evidence against multiple glaciations in central Alberta.

Topographic Setting

The study area occupied the preglacial drainage divide between the Vermilion and Wainwright valleys (Figure 4.1b) named the Viking upland (Chapter 3). The KGC was situated in the middle of the bedrock-controlled Viking upland (Figure 4.2) defined by the 700 m contour and rises 20-40 m above the surrounding terrain. This upland was dissected by several troughs and shallow depressions, some of which contained channels. The largest trough was oriented north-south and connected with the Birch Lake depression to the north. It contained the channel that connected directly to the KGC. This north-south oriented trough extended south of the KGC but glaciofluvial channels in that area were oblique to this orientation. Multiple channels occurred west of this topographic feature but few were present to the east.

Because the study area occupied a topographic divide, the slopes opposed one another between the southern and northern areas. Although this generally is true, the main trough that dissected the upland sloped to the south with only the most northern extents having an opposing slope. The upper surface of this upland was generally flat with undulations in the underlying bedrock mantled by a relatively thin amount of glacial sediment. The trough did not exhibit any morphologic or sedimentologic characteristics that might indicate bidirectional flows along its length.

Observations

This paper focuses on the morphology and sediments associated with the KGC and is divided into three parts. The first section will outline some of the most pertinent characteristics of channels that contributed sediment to the complex. The second will concentrate on the architecture and surface morphology of sediments contained in the KGC. The third section will illustrate landforms and sediments of the main outlet to the KGC.

Landforms and Sediments in the Northern Inlet Channel

Site #1

This exposure was located in the northern part of the study area along the eastern edge of a well-developed hummocky belt, adjacent to a broad zone composed primarily of glaciofluvial sediments (Figure 4.2). A few kilometres north of this location, an esker overlaid glaciofluvial sediments that were continuous with the sediments at this site. These glaciofluvial sediments onlapped the hummocky terrain along both margins, locally muting the expression of the hummocks. Glaciofluvial sediments were present within the hummocks as well as in the inter-hummock areas. The exposure was located on the southeast margin of an elongate hummock. In addition to the main exposure, several test pits had been dug in the inter-hummock area. These test pits were up to 3 m deep and indicated that glaciofluvial sediments were widespread even on other hummocky features in the area. The western and northwestern margins of the main hummock contained diamicton at the surface.

Three main facies were found within this elongate hummock (Figure 4.3). First, diamicton formed the core of the landform and was also intercalated with gravels and sands along the margin (Figure 4.3a). Second, bedded gravels dominated the northeast part of the landform and in the inter-hummock areas (Figure 4.3b). Third, intercalated diamicton and glaciofluvial sediment dominated the southeast margin, particularly the steepest slopes (Figure 4.3c). Diamicton, in the core of the hummock, was dense with intermediate stoniness (Figure 4.3a). Sand and fine gravel partings were present. The upper contact of the diamicton was typically scalloped and intraclasts composed of this diamicton were commonly suspended in the gravels. The lower contact of the diamicton core was not exposed.

The best-exposed gravels, up to 4 m thick, were along the northeast portion of the landform and were planar-bedded (Figure 4.3b). The gravels were imbricate and indicated no post-depositional disturbance. Cross-bedded gravels were present near the elongate hummock but were only exposed

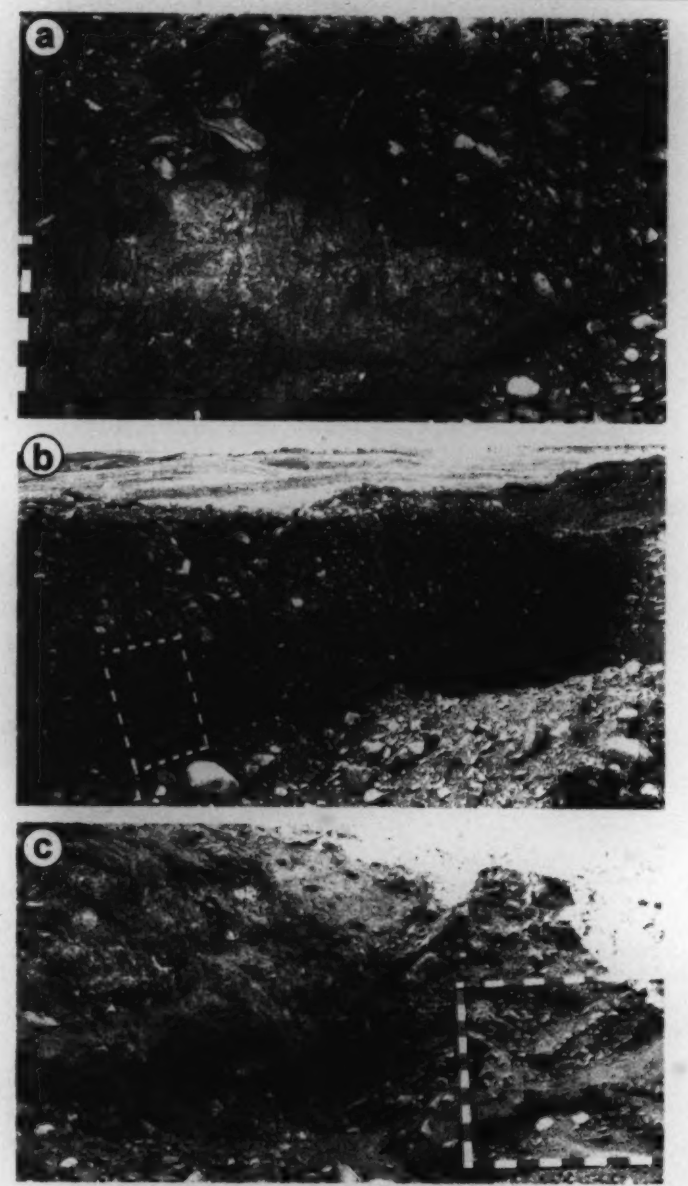

Figure 4.3: Sediment types at Site #1. (a) The core ogthe elongate hummock was composed of a stone-poor, compact diamicton. The upper contact of this unit was typically scalloped and overlain by bedded gravels. (b) Perched near the top of the hummock were planar-bedded gravels. These gravels did not indicate significant post-depositional disturbance. (c) Along the E and SE margin of this hummock the diamicton and gravels were intercalated, indicating significant slumping/flowage of both units. Scales have decimetre divisions.

in test pits. Paleocurrent estimates in these gravels indicated flow toward the southwest.

Contacts between the intercalated diamicton and gravel typically paralleled the slope of the landform. Units of diamicton and gravel were arranged in wedge-shaped units. The bedding was often interrupted by overturned folds and attenuated beds indicating significant slumping. Planar-bedded gravel and boulders were present, but the bedding had often been disturbed and near-vertical beds of imbricate gravel were common. Rapid lateral and vertical changes in composition and bedding attitude were common (Figure 4.3c). Within the intercalated diamicton and gravel were intact inclusions of gravel that display reorientation of clasts along the margins (most common on the downslope margin). Where sand partings were present in the diamicton, they were attenuated. Rare laminated intraclasts were present. The overall tendency was toward a homogenization of the sediments into a very stony diamicton.

Site #2

This exposure was located 300 m southwest from Site #1 (Figure 4.2). It was part of an undulatory hummocky feature with a steep slope on the west and north and a gentle slope toward the east. This eastern slope was dominated by bedded boulders, gravel, and coarse sand. This hummocky landform was flanked on the south by a wide glaciofluvial channel and on the west and north by well-developed hummocky terrain. The top of this feature had been mined for aggregate and one test pit had been dug in the inter-hummock depression on the north side.

The arrangement of the sediments was chaotic and indicative of widespread slumping. Slickensides, present in a few locations, recorded differential movement between units. Six units were identified. The lowest unit (Unit 1) was massive to planar-bedded gravels and sands. This unit was exposed in the main excavation and also in the test pit on the northern flanks (Figure 4.4a). The bedding planes dipped to the west and contained normal faults. The faults dipped to the east but were inaccessible for further investigation. Unit 1 was overlain by laminated silts and fine sands (Unit 2). This unit had an undulatory, erosional upper contact and was often significantly deformed, though sometimes the laminations were still visible (Figures 4.4b and c). This unit contained some small pebbles but was generally stone-poor. Also, several normal faults dipped toward the northern flank of the landform. Unit 3 was composed of massive, coarse sand and was poorly expressed in the exposure. Unit 4 was composed of matrix-supported pebble to cobble gravel. The upper contact of unit 4 was usually defined by a silt drape but where this drape was not present, the unit exhibited evidence of slumping. Gravel-sized clasts dip into the face at approximately 307°. Unit 5 was

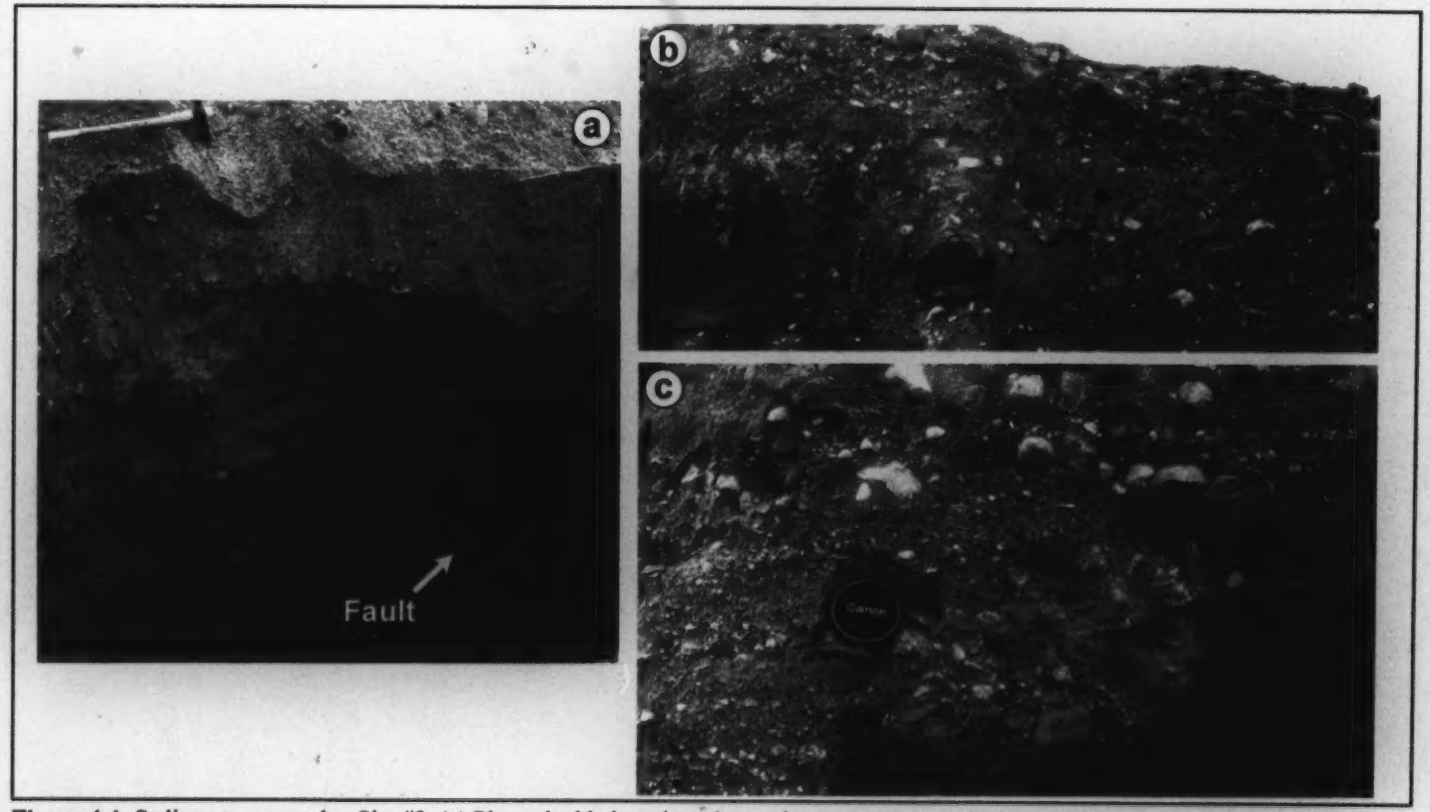

Figure 4.4: Sediments exposed at Site #2. (a) Planar-bedded sands and gravels were present at the base of the exposure and in the interhummock areas. These sediments contained normal faults. Pick handle is approximately 1 m long. (b) The upper parts of the exposure was characterized by laterally discontinuous units ranging from fine-grained (almost diamictic) laminated sediments that were highly deformed, and associated with normal faults, to clast- and matrix supported gravels/boulders. (c) In places the laminations in fine-grained sediments were preserved. The erosional contacts were very prominent and the fine-grained sediments were present as intraclasts in the coarser sediment.

composed of massive, coarse sands, large cobbles and planar bedded sands. This unit graded upward into Unit 6 which was dominated by chaotic, clast-supported gravel. The fabric of this gravel was highly variable.

Laterally, the arrangement of the units changed dramatically. Slumps were more frequent along the northern part of the exposure. One major fault with slickensides was oriented toward 305° and plunged at 45°. Displacement along the faults was up to 0.75 m and tended to increase toward the northern side of the hummock. Small rip-ups of the laminated silts and sands (Unit 2) were present in overlying gravels (Figure 4.4c). Southward along the exposure, planar-bedded sands capped the landform and indicated flow parallel to the landform. Also, the contact between Units 1 and 2 changed from an orientation of 150 to 300° and a plunge of 42 to 33° toward the south.

Site #3

This site was part of the continuous glaciofluvial system that connected to the KGC (Figure 4.2). It was located along an northeast-southwest arcing section of this system. To the northeast there were several parallel arcuate ridges, composed of glaciofluvial material, which were part of this continuous system. Well-developed hummocky terrain to the west and east was truncated and superimposed by glaciofluvial sediments. Large depressions interrupted the hummocky terrain to the west, where large lakes such as Lac Loranger and Camp Lake are located (Figure 4.2). The relief of the hummocks was superimposed on a gently sloping surface that confined the glaciofluvial system. This trough was narrow at the location of Site #3.

The main pit exposure had been excavated into a ridge that roughly paralleled the orientation of the glaciofluvial system and Lac Loranger. This ridge was located along the western flank of the glaciofluvial sedimentation and provided the eastern margin of Lac Loranger. Two main pits will be described. The first was cut into the top of the ridge, roughly perpendicular to the long axis of the feature. The main characteristic of this pit was that the sediments conformed to the shape of the landform and therefore could not be associated with the removal of a supporting ice wall (Figure 4.5a). The second pit was located along the southeast slope of the ridge and the eastern part was cut into the lowest glaciofluvial gravels within the channel.

This upper pit was dominated by planar-bedded sands and gravels that dipped to the lateral margins of the feature (Figure 4.5a). The ridge was superimposed by numerous bumps that, coupled with the bedding in the ridge, indicated bedforms were present in the formative environment. The gravels were clast-supported and imbricate. Estimates of the paleocurrents from the imbrication

Figure 4.5: Sediments exposed at Site #3. (a) The upper pit was dominated by planar-bedded sands and gravels with secondary occurrences of cross-bedding. The bedding planes in this pit conformed to the shape of the elongate landform indicating that the landform was a primary form. (b) Sediments in the lower pit were dominated by dipping beds of gravels and sands which paralleled the shape of the landform. A lacustrine cap thickened to the right (east). (c) Sediments of the southern face (opposite of beds in b) had a higher component of sand with syndepositional disturbances. In some places minor normal faulting was present.

indicated flow toward the southwest although the dispersion increased toward the margins of the feature. Clasts up to 0.5 m in diameter indicated powerful flow velocities. The texture of the gravels was coarser, and there was some cross-bedding, toward the crest of the ridge compared to lower in the sequence. Units of planar- and cross-bedded gravels were commonly 0.5 m thick although some were thicker. Erosional contacts were common but gradational contacts were also present. Evidence for post-depositional faulting was not present and thus the "arched" architecture of the sediments represents the primary bedding attitudes.

The lower exposure was dominated by three facies. First, were planar-bedded gravels with secondary, cross-bedded sands. Bounding surfaces conformed to the shape of the landform (Figure 4.5b). The gravels/sands were rhythmically bedded with the gravels comprising most of the sediment. The gravels were clast-supported, imbricate and fairly well-sorted. Some tabular cross-bedding was present. Second, rhythmically laminated silt and clay unconformably overlaid the gravels. The rhythmicity of the laminations was poorly-developed higher in the section where they were overlain by aeolian sands. The rhythmite set was up to 3 m thick toward the east (into the thalweg of the valley). The third facies was dominated by planar-bedded sands with laminated fine sands. This facies dominated the southern pit faces only, overlying clast-supported gravels. The sediments were well-sorted and some units were bimodal with small pebbles and well-sorted sands. Often, fine sediments were interbedded with thin gravel beds. Contacts between these units were erosional but some gradation was present between the sand components. Overall, the bedding dipped to the southeast, although there were local departures from this trend.

Sediments along the southern exposure are indicated in Figure 4.5c. The base of this face was dominated by planar- to crudely-bedded gravel. Higher in the section, the gravels were interbedded with plane- to cross-bedded/laminated sands and fine sands. Roll-up structures were present, indicating syndepositional disturbance. Silt laminations were present within some sand units and often draped the underlying gravels. The presence of these fine laminae indicated that coarser-grained deposition was punctuated by periods of relative quiescence. In some instances, cobbles had been forced up into the overlying sediment. Highly-fractured sand units and the presence of sand intraclasts attest to the erosion/incorporation of the finer sediment into overlying, coarser units.

The most striking characteristic of the sediments contained in the lower pit were the post-depositional features. First, minor slumps occurred during deposition of sediments exposed on the southern face. Second, normal faults were present but not pervasive. These small faults seldom indicated displacements greater than 3 cm. The cumulative displacement from all the faults was not

sufficient to explain the morphology of the ridged landform. Third, there were several features indicating that disturbance by periglacial processes came after deposition of the glaciofluvial sediment. Three such features present in this lower pit indicated that periglacial activity postdated deposition of the sediments. First, one ice-wedge pseudomorph was present on the northern part of the pit along the lower slopes of the ridge (Figure 4.6a). Clasts adjacent to the ice-wedge are realigned parallel to the feature due to the lateral cryostatic forces (Washburn 1980). The clasts were turned downward and the extent to which the clasts had been realigned was limited to a zone <30 cm from the contact. This transition zone was greater near the bottom of the feature. The sediments that infilled the pseudomorph were indistinguishable from the lacustrine sediments that overlaid the gravels in the rest of the pit. The pseudomorph contained two distinct types of sediment that were consistent with the sequence outside the wedge feature (Figure 4.6a). The lower part of the sediment was lighter coloured with finer, darker coloured sediment in the middle of the infill. The laminations within the infill had been deformed, presumably during the process of infilling. Second, the rhythmites that overlaid the gravels in the entire pit were usually cusped (a in Figure 4.6a). This cusped nature of the sediments was less evident closer to the top of the exposures and was usually indistinguishable further than 1 m from the gravel contact. Third, in several locations, small amounts of gravel had been lifted relative to the other gravel in the unit (Figure 4.6b). The gravels appeared to have been 'popped-up' by cryostatic forces. These features were 2-3 m across, and rose up to 0.75 m above the main gravel unit. Near the contact with the overlying silts and clays, the clasts in the elevated features were parallel to the contact, but this did not extend very far laterally. The clast-supported gravels within the features appeared to be only minimally disturbed. Along the margins of some features was evidence of lateral movement in addition to vertical movement. The clasts in the gravel and the overlying silts and clays were turned over in a fold (a in Figure 4.6b). Usually, the laminated silts and clays were continuous over the elevated gravels, although the laminations were discontinuous at some locations. The disruption in the laminated sediments was not evident higher in the section, indicating that the upper portions of the laminated sediments post-dated the disturbance. In addition, the aeolian sediments that cap the sequence did not mimic any of the disturbances present in the gravels and laminated sediments.

Site #4

This site was located 400 m to the southeast of Site #3. The pit at this site was excavated into an elevated bench along the margin of the glaciofluvial channel near the contact with the

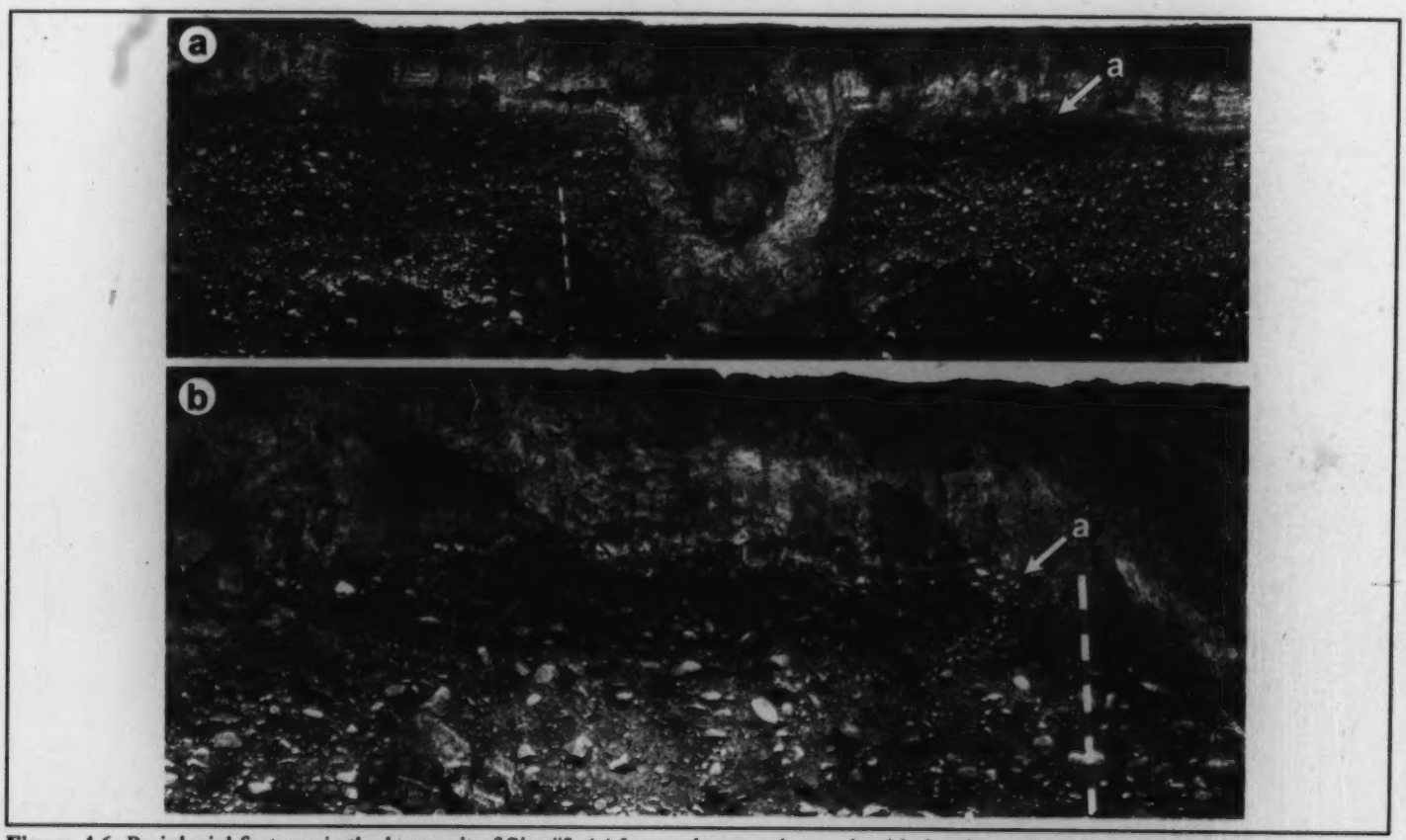

Figure 4.6: Periglacial features in the lower pit of Site #3. (a) Ice-wedge pseudomorph with the clasts aligned parallel to the fine-grained infill sediment. Note the cusped nature of the lacustrine rhythmites (a). The gravels were usually planar-bedded, apart from the periglacial features. (b) Portions of the gravel unit have been elevated. Note the coherence of the imbrication even in the elevated portion and the overturned fold (a). The overlying laminated sediments conformed to the elevated gravels. Scale divisions are in decimetres.

hummocky terrain (Figure 4.2). The surface of this bench was characterized by low-amplitude hummocks. Immediately north of this location the eastern margin of the glaciofluvial channel possessed subparallel ridges that contained glaciofluvial sediment. Within 50 m of this location the hummocky terrain is dominated by compact till with some sandy lenses.

The sediments at this location were dominated by large-scale cross-bedded sands with a minor gravel component (*cf.*, Figure 3.7b). The site contained large, trough-cross-bedded units of well sorted sands and, occasionally, planar-bedded foresets. The contacts were erosional and many of the units contained a lag of pebbles, along the lower contact, that were often imbricate. The foresets dipped to the west-southwest indicating paleocurrents parallel to the side of the glaciofluvial channel. Intraclasts of diamicton were contained in some cross-bedded units. The entire sequence was capped by laminated silts and fine sands. Minor normal faulting was observed but the displacement along fault traces was insignificant and the lack of staining along the traces indicates that they may be associated with the pit excavation.

Site #5

These exposures were located south of the previous sites within the main glaciofluvial channel (Figure 4.2). Between Sites #3 and #5 the surface of the glaciofluvial sediments had a low-amplitude hummocky appearance with a single paleochannel. A large bar-shaped form caused the channel to bifurcate. The two sites were located on the northern and southern edges of this bar-form. This bar-form was cored by diamicton and appeared, therefore, to be an erosional remnant superimposed by the gravel deposits. The southern exposure was located in a trough along the southern edge of this residual, whereas the northern exposure was cut into the northern end of the residual. The surface of this residual sloped gently to the east where the eastern segment of the glaciofluvial channel was narrow. The western margin of this residual was sharply defined and appeared to have been truncated by glaciofluvial erosion. Hummocky terrain flanked either side of the glaciofluvial channel that delineates this residual.

The northern exposure was characterized by trough cross-bedded gravels, interbedded with cross-bedded sands (Figure 4.7a). Planar-bedded units were present but did not constitute a significant component of the exposed sediment. Gravel units were clast-supported and often contained cobbles and small boulders, though they varied from matrix-supported to open-work. The bedding of the gravel units was not coincident with the morphology of the landform but rather had been truncated to create the landform shape. The contacts between the cross-bedded units were

Figure 4.7: Examples of sediment at Site #5. (a) Sediments exposed on the northern end of the bar-like landform. The sediments were dominated by cross-bedded gravels. The bedding indicated paleoflows over the top of the bar form. The shape of this landform was not defined by the bedding of the sediments because they have been truncated. (b) Sediments in the southern exposure were dominated by bouldery gravels, and planar-bedded gravels with a secondary component of cross-bedded gravels/sands. Scale divisions in decimetres.

erosional. The bedding generally dipped to the south or southwest but this was variable. The gravel units were thicker than the sand units, typically up to 1.5 m thick. Estimates of paleocurrents from cross-bedded gravels indicated that the formative flow was toward the south-southwest (i.e., over the length of the residual) (*cf.*, Figure 4.2).

Sediments in the southern exposure were dominated by planar- and cross-bedded cobble gravels with minor sand units (Figure 4.7b). Imbricate, cobble gravels were dominant in the exposure and indicated formative flow toward the southeast to south. Cross-bedded sand units contained pebbles. Some broad, erosional troughs cut into the gravels were infilled with planar-bedded sands.

Other Characteristics of the Northern Inlet Channel

The channel that connects the sites, indicated above, narrowed and became better defined southward. Near its entrance to the KGC, the channel had high terraces that superimposed the hummocky terrain. These terraces were composed of bouldery gravel with chaotic and planar-bedded units, but the composition was highly variable. The channel was incised up to 5 m into these sediments and had a low gradient (Figure 4.2). In addition to the terraces, there were perched glaciofluvial sediments on the interfluves between this main inlet channel and the erosional bedrock channels to the west. Such sediments were commonly located in saddles of the interfluves between these channels. Perched glaciofluvial sediments overlaid the diamicton or bedrock that characterized the interfluves. Perched sediments indicated that there had been a connection between the two systems and that the channels had operated contemporaneously.

Large striated boulders were found in the main channel. The delicate striations were preserved even though the boulders must have been transported at least some distance because they were situated on top of glaciofluvial sediment. The striated boulders exceeded 3 m in diameter (Figure 4.8a). Boulders of this size were found associated with many of the exposures along this channel (Figure 4.8b).

In the main channel, immediately north of the connection with the KGC, the glaciofluvial sediments (dominated by large boulders and coarse gravel) directly overlaid bedrock. At this location a large terrace of glaciofluvial sediment was elevated several metres above the thalweg of the inlet.

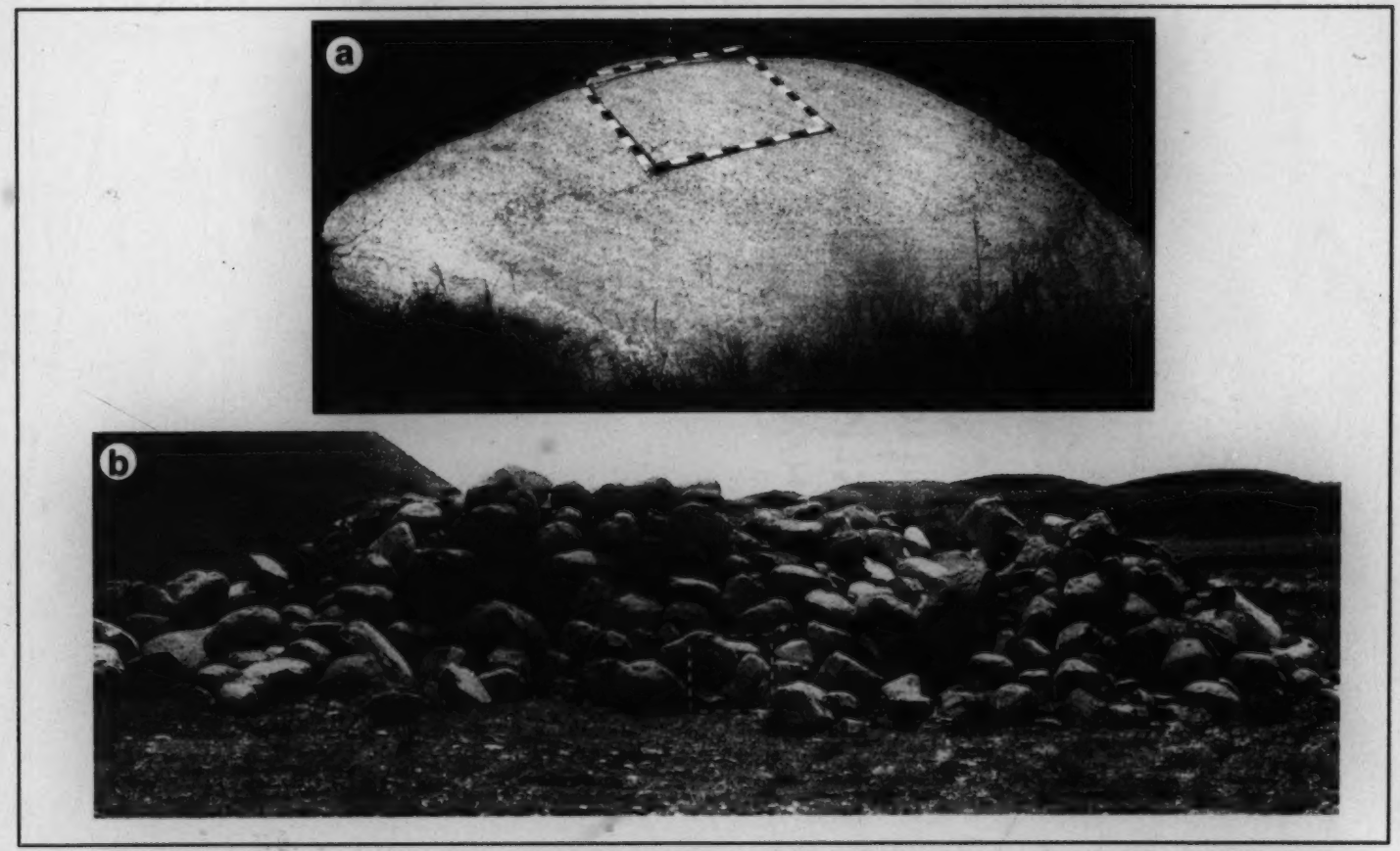

Figure 4.8: Large boulders found in the glaciofluvial channel that connected with the KGC. (a) Large striated boulder with delicate striations on the upper, faceted side. This boulder was found within the channel on top of glaciofluvial sediment. (b) Oversized boulders accumulated from an excavation into a glaciofluvial terrace. Boulders often possessed significant rounding, although angular boulders were also present. Scales have decimetre divisions.

Landforms and Sediments of the Western Inlet Channel

The western inlet was a single, slightly sinuous trough that extended from the western margin of the hummocky terrain that defines the Viking 'moraine' (Figures 4.2 and 4.9). This trough was a continuous zone where the hummocky terrain was muted by the superimposition of shallow glaciofluvial sediments. The sediments in this trough were continuous with the KGC on the western side. The continuation of the trough on the eastern side of Hattie Lake was one of the channels that separated the different lobes of the KGC. On the eastern side of Hattie Lake, the hummocks were composed of diamicton that were often covered by boulder lags or thin mantles of bouldery gravels.

The exposures in this area were in poor condition and shallow due to the proximity of bedrock. The glaciofluvial sediments ranged from planar-bedded, well-sorted sands to chaotic and planar-bedded gravels. A faintly-laminated diamicton was intercalated with chaotic, clast-supported gravels on the northern margin of this inlet channel. It appeared that this diamicton was a raft of material eroded/deposited during utilization of the channel. Boulders over 3 m in diameter were found in the sediments and, particularly, high on the sides of the channel. The glaciofluvial sediments were superimposed by lacustrine deposits.

One of the most important aspects of this inlet was that there were eskers superimposed on the landform. The best example of an esker is found in the middle of the channel, west of a constriction formed by large hummocks. The crest of the esker was approximately 2-3 m high and sinuous over much of the width of the channel. In addition, there were several indistinct, discontinuous, esker segments between this well-defined segment and the confluence of the channel with the KGC. The presence of the eskers on top of the glaciofluvial sediments and the hummocky terrain indicates a very different timing of formation of these landscape elements than has been inferred earlier (Gravenor and Bayrock 1956; Gravenor and Ellwood 1957).

The Kinsella Glaciofluvial Complex

Setting of the KGC

The KGC occupied a shallow basin that is part of a trough that extended from the Birch Lake depression to the north, southward toward the Sedgewick district (Figures 4.2 and 4.10). This basin represented a major lateral expansion of this north-south depression and was associated with a regional deflection of erosional glaciofluvial channels (*cf.*, Chapter Three). The KGC represented a major depositional zone, because of the lateral expansion of inflowing water, and was arranged into three depositional zones (lobes), defined by east-west oriented channels. Hummocky terrain and

Figure 4.9: Setting of the western inlet channel. A broad glaciofluvial trough cuts through the hummocky terrain. Sediments onlapped the hummocks at the margins. In several places the glaciofluvial sediments were superimposed by eskers (indicated by arrows). These eskers were not situated along the thalweg but, rather, were perched along the margins. This trough is continuous with the KGC.

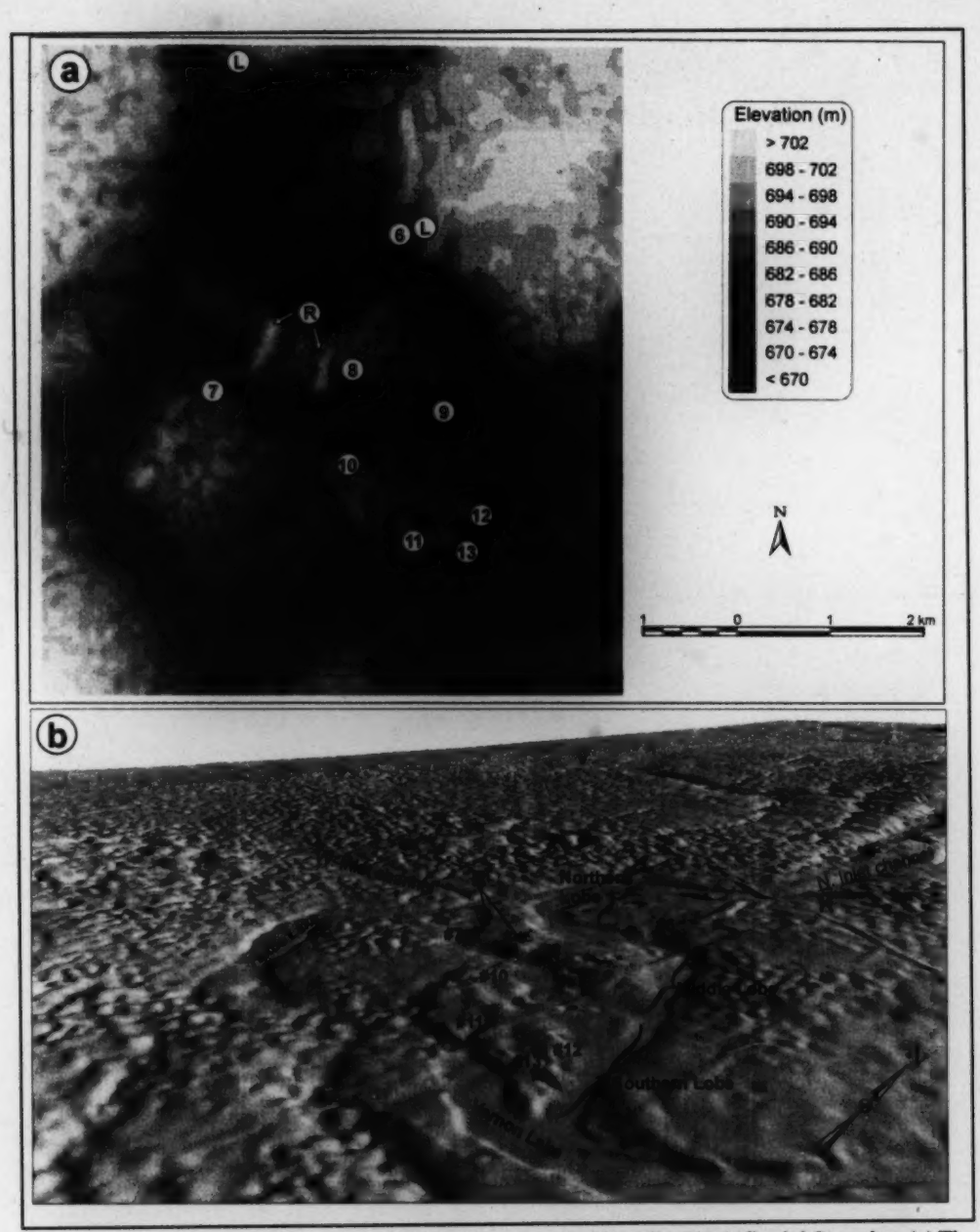

Figure 4.10: The topographic setting of the sediments in the Kinsella Glaciofluvial Complex. (a) The shallow basin that contained the KGC is flanked by perched lacustrine sediments in at least two places, "L". Note the large ridges at "R" and site locations described in the text. (b) Perspective plot of the KGC indicating the sites numbers described in the text, large ridges (R), and the three main lobes of deposition. These lobes are separated by channels of which only the northern one presently conveys flow. K-Kinsella, V-Viking.

linear ridges were found in direct contact with the sediment within the complex. Glaciofluvial sediment onlapped the hummocky terrain along the margins and this superimposition was associated with a muted expression of the hummocks. In some places the glaciofluvial sediments extended above the height of the surrounding hummocky terrain, and several metres above the hummocks contained in the glaciofluvial channels to the south (Figure 4.10). It is clear that there were only a few **channelized** inlets to the complex; the morphology and sediments were described in previous sections. The western edge of the complex is characterized by hummocky terrain, dominated by fine-grained till. North-northeast to south-southwest oriented ridges were associated with these hummocks and rise 8-10 m above the hummocks and the glaciofluvial sediments. The glaciofluvial sediments overlaid the hummocks and the channels truncate them.

The main depositional zones are arranged in lobes, dissected by west-east oriented channels. These channels commonly have exposed bedrock along the floors, or thin alluvium. The western margin of the complex is defined by Hattie Lake and the eastern margin by Vernon Lake. These lakes were shallow and saline and, of the connecting channels, only the northern channel flows during spring floods. The middle channel was perched above Hattie Lake on the western end and merged with Vernon Lake to the east. The channel that defined the southern margin (southern extension of Hattie Lake) of the complex, curved abruptly toward the east-southeast, after which it has hummocky terrain along the bottom. This hummocky terrain is continuous with the hummocks on the interfluves and the high-relief hummocks to the west of the KGC.

The KGC had been mined for aggregate for several decades and is the primary source for towns as away as Ryley (70 km to the northwest). Although the area has been extensively mined, the exposures were generally poor and shallow (due to the proximity of bedrock). The following site descriptions refer to those exposures that were fresh in the summers of 1994 and 1995.

Site #6

This site was located on the northern lobe of the KGC, immediately south of the primary channel inlet (Figure 4.10). The site consisted of two pits, positioned on a surface that slopes gently toward the west. The morphology of this surface vaguely resembled a point bar in a meandering river. Several troughs cross-cut this surface and disrupted the point bar appearance. Postglacial stream channels had eroded the northern margin of this part of the KGC. On the highest point of this lobe, a sinuous landform linked the main inlet channel and the northern end of Vernon Lake. The landform was generally flat-topped, with several small depressions. A secondary ridge joined it near

the northern end. The crest of the landform sloped toward the south where it ended at Vernon Lake. This feature was elevated above the rest of the glaciofluvial sediments in this part of the KGC and appeared to superimpose the east-west trending component of the complex. It was flanked by troughs that were hummocky for its entire length (Figure 4.11). This landform was composed of sand to boulders and had an extensive excavation on the southern end. The local topographic relationships are shown in Figures 4.10 and 4.11. Pit A (Figure 4.11) was situated east of the sinuous landform and flanked by lower-elevation hummocky terrain. Pit B was located on the southern end of this sinuous landform near the east-west trending channel that connected with Vernon Lake.

Pit A was situated on the flanks of the esker-like landform 3-4 m higher than Pit B. The exposures in this pit were limited to north-south oriented faces. The surface at this location, was transitional between the esker-like landform and the hummocky terrain (dominated by diamicton). This pit was dominated by two main facies; laminated silts and fine sands and cross-bedded gravels. The laminated silts and fine sands were either found in one laterally continuous unit 1-1.5 m thick (Figure 4.12a) or as perched intraclasts. These sediments were rhythmically laminated. Fine sand laminae were up to 5 mm thick and the silt laminae were thinner. This unit contained a few dropstones and possessed deformation consistent with that interpretation (Figure 4.12b). Laminae in the upper 10-15 cm were typically deformed with overturned folds (Figure 4.12a and b). This deformation indicates the application of shear to the sediment, but it was insufficient to homogenize the sediment. The lower contact of the unit is conformable; the laminae drape the underlying gravels. The upper contact is erosional and usually overlain by a cobble/pebble lag (Figure 4.12a, left side).

The laminated sediments overlaid a unit of cross-bedded gravel and boulders with some vaguely planar-bedded gravel/boulders (lower unit in Figure 4.12a). Boulder clusters and graded cross-beds were present. The depth of these sediments could not be determined. This unit was laterally continuous with crudely-bedded gravels and boulders on the north side of the pit (Figure 4.12c). Boulders were rounded to sub-rounded and consisted of Cordilleran and Canadian shield lithologies. The crudely- to cross-bedded gravels and cobbles graded up into sands and silts that were indistinguishable from the lacustrine unit already described. Interspersed with the coarser fraction, were lenses of cross laminated, well-sorted sands that have been truncated by the coarser sediments.

Pit B exposed sediments of the esker-like feature and the adjacent surface (Figure 4.11). Exposures on the eastern side of the pit/feature are dominated by diamicton and bedded gravels. One diamicton unit is bounded below and above by gravels. At the southern end of the section, diamicton dominated the section with a shallow unit of gravel on top. At the southern end of the exposure, the

Figure 4.11: The setting of Site #6. Pit A was situated on high ground and was cut into a low-amplitude ridge. East of this location hummocky terrain was composed of diamicton. Pit B was situated on the southern extent of a sinuous, esker-like feature. The white lines indicate where pit faces were situated in 1994 and 1995. Paleocurrents taken from the west side of Pit B are indicated. Clast fabric from the diamicton in the lower pit is indicated.

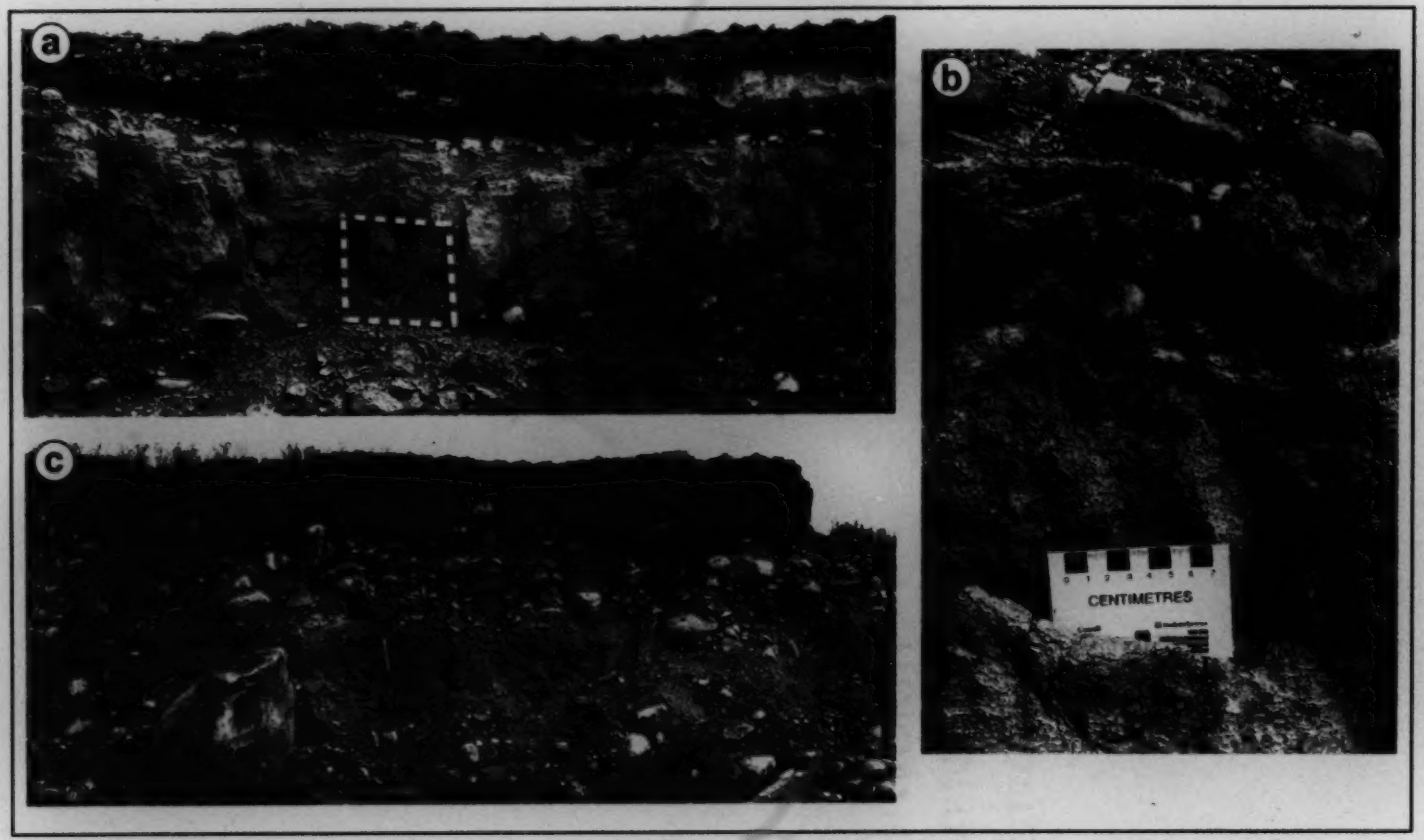

Figure 4.12: Sediments present at Site #6, Pit A. (a) Laminated silts and fine sands draped underlying cross-bedded gravels and were unconformably overlain by a thin unit of cross-bedded sands/gravels. (b) The laminated sediments contain many structures indicating minor deformation near the upper contact. Note the deformation of the laminae around the clast above the scale. (c) Vaguely-bedded gravels/cobbles truncate cross-laminated sands. Boulders with diameters greater than 1.5 m are present. The shovel is approximately 1 m long.

lower contact of the diamicton was not visible, but the upper contact was erosional (scalloped upper surface). The upper gravels were vaguely-bedded, imbricate, and capped by aeolian sediment. The diamicton was of intermediate stoniness, generally massive with faint laminations near the top of the unit. The unit was usually 1-2 m thick. Near the northern end of this exposure, a lower unit of planar-bedded gravels was present beneath the diamicton (Figure 4.13a). Overall, the lower gravels were finer than those above the diamicton. Lens-shaped pods of diamicton were contained within the lower unit of gravels. Also, the lower gravels have been intruded/folded into the overlying diamicton. The folded diamicton/gravel contact was occasionally overturned. The diamicton has a homogeneous appearance near the base but near the top appears to be laminated. The upper contact of the diamicton unit was scalloped, as it is further south (Figure 4.13b).

Exposures in the middle of the esker-like feature (Figure 4.13c) were dominated by two facies; large-scale, trough cross-bedded sands/gravels and crudely-bedded gravels and boulders. The cross-bedded sands were well-sorted with pebble lags along the bounding surfaces. Individual sets were 1-1.5 m thick for a total thickness of >5 m (the lower contact is not visible). Coal fragments were found within many of the units. Paleocurrent estimates indicate flow toward 240°. These cross-bedded sands were overlain by approximately 1 m of crudely-bedded gravels/boulders, separated by an erosional contact. The lowest unit of cross-bedded gravel was exposed in only a few locations. This unit was gradational with the overlying cross-bedded sands.

Sediments exposed on the western side of the esker-like landform and the adjacent trough shared a consistent architecture. There were many clasts, ranging from subangular to subrounded (tendency toward subangular), greater than 2 m in diameter. These large clasts were of Canadian shield origin. Trough cross-bedded sands/pebbles similar to, and probably continuous with, the trough cross-bedded sands indicated in Figure 4.13c, dominated the upper part of the section. This unit was unconformably overlain by large-scale, cross-bedded gravels and crudely-bedded/imbricate gravels and boulders near the top of the exposures (a in Figure 4.14a). The lower contact of these sandy cross-beds was either erosional or gradational. Where the lower contact was gradational, the lower sediment was composed of normally-graded, cross-bedded to planar-bedded gravels. Boulders were also found in this lower unit. Paleocurrent estimates from the cross-beds indicated flow toward the south, whereas the lower unit was deposited by flow toward the west-southwest. Rapid changes in the paleocurrents were associated with the southeast curvature of the landform (Figure 4.11). Often the grading in the lower unit ranged from openwork pebbles to sorted sands (Figure 4.14b). Along the western margin of this sinuous landform, the attitude of the bedding planes were

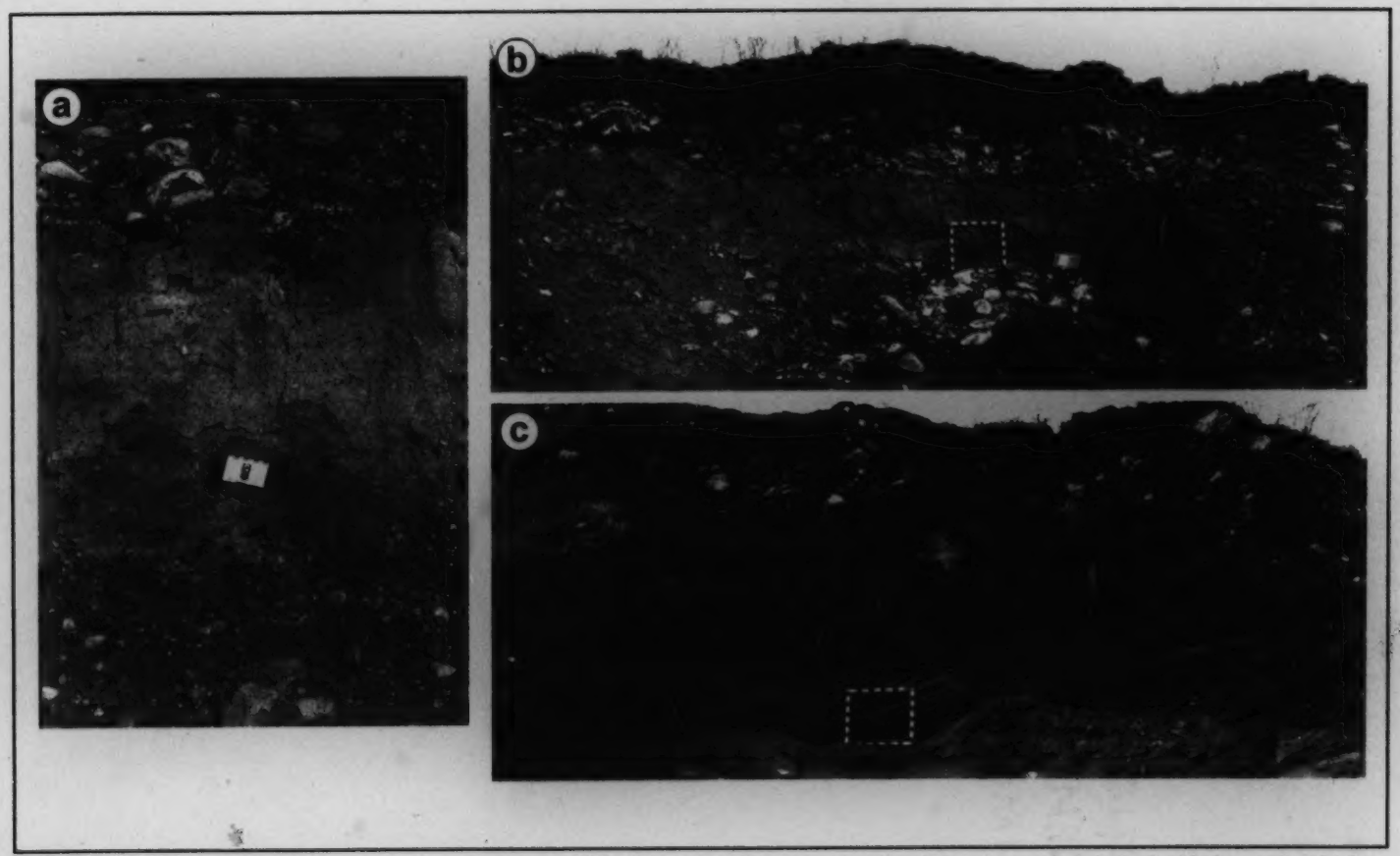

Figure 4.13: Sediments in the central and western part of Site #6, Pit B. (a) Stone-poor diamicton was underlain by bedded gravels which have been folded into the diamicton. These folds were sometimes overturned. (b) The same diamicton unit as in (a). The upper surface is scalloped. The diamicton has faint laminations in the upper part. (c) The central part of this esker-like landform was dominated by trough cross-bedded sands with a cap of chaotic to vaguely-bedded gravels. The scales have decimetre divisions.

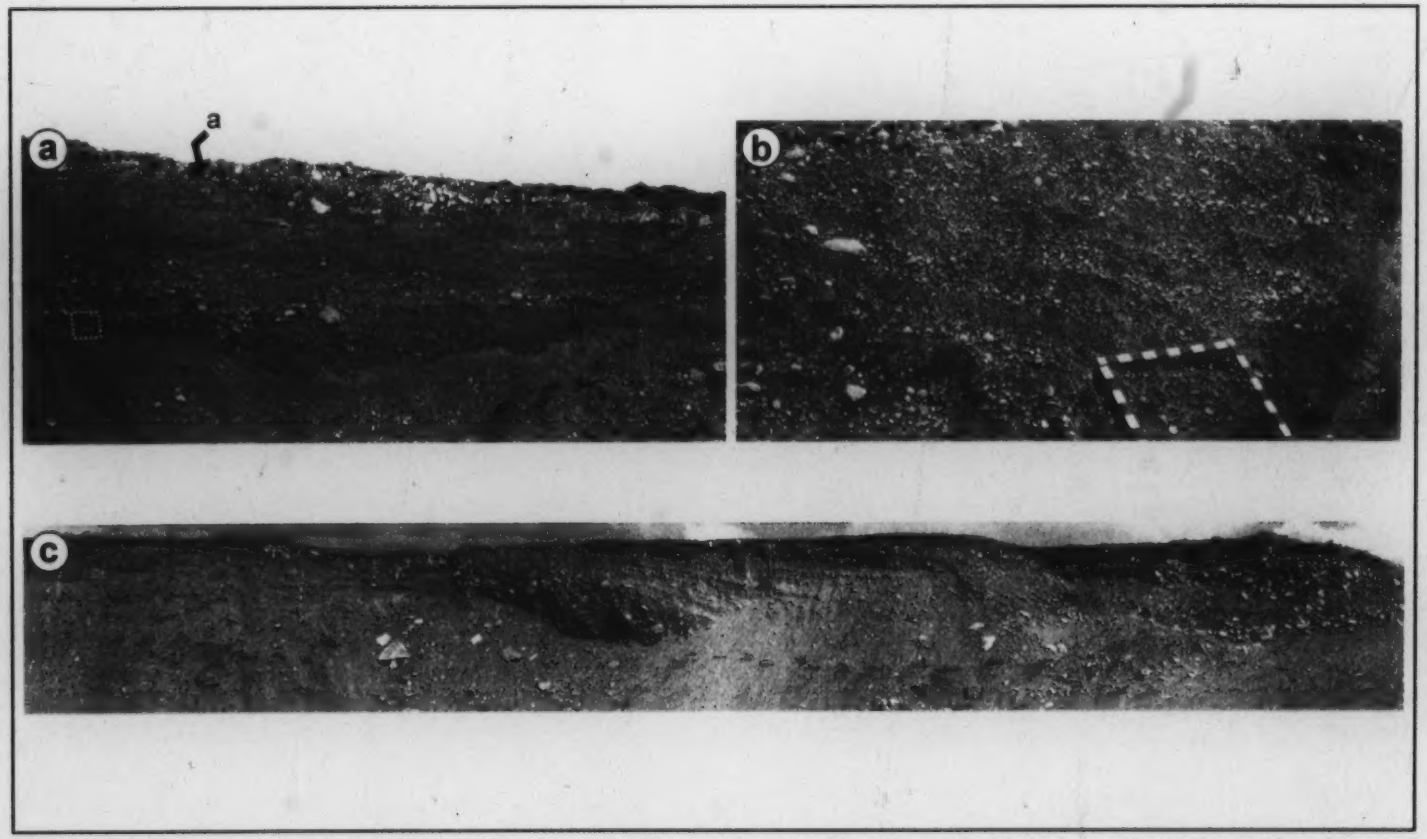

Figure 4.14: Sediments along the western margin of the esker-like landform. (a) Trough cross-bedded sands and gravels constituted most of the lateral margins of this landform. Note the truncation of the cross-bedded sands by the gravel at (a). (b) Graded cross-beds ranging from openwork pebbles to coarse sands. These sediments were located near the base of the section. (c) Panoramic view of the northern exposures. Note the lateral change from trough cross-bedded sands on the left to gravel cross-beds on the right. The scales in each figure have decimetre divisions.

coincident with the slope of the landform.

Along the northern part of the pit (Figure 4.11), sediments are exposed in the western margin of the esker-like landform where it slopes to the west. There were several different units present at this location (Figure 4.14c). The first unit consisted of large-scale, trough cross-bedded, well-sorted sands that were succeeded laterally by a southward dipping unit of bouldery gravel. This heterogeneous unit of gravels contained clasts oriented parallel to the bedding planes, in addition to chaotic melanges of gravel to boulder sized clasts. The lower contact with this unit was erosional and dipped steeply. This chaotic unit graded laterally into large-scale, cross-bedded, sand and gravel. This unit graded laterally into clast-supported boulders that contained little finer grained material. These boulders were imbricate and sub-rounded.

All the units, described above, were consistent with the shape of the landform. The dip angles of the units were roughly parallel to the slope of the landform. The arrangement of the different units indicated a complex depositional history. Although the arrangement of the units was complex, several general trends were present. First, the cross-bedded sands were always situated near the top of the sequence, though they had been truncated by chaotic gravels in places. Second, relatively thin units of chaotic gravel that cap the sediment sequence overlaid an erosional contact. Third, because there had been minimal post-depositional modification of the sediments (in the form of normal faulting or gravity flows), the concurrence of the bedding and morphology of the sinuous landform were primary features. Fourth, the architecture of the sediments indicated that sedimentation was in the form of large 2-D and 3-D dunes.

Surface morphology of the southern KGC

The surface of the KGC, south of Site #6 (middle and southern lobes), was characterized by numerous arcuate/subparallel ridges (Figure 4.15). These ridges were more pronounced near the northern inlet channel than further south, but were visible on the ground. The linkage between the morphology of these ridges and the glaciofluvial sediments is critical to the thesis of this paper and will be emphasized in the following sections.

Site #7

Figures 4.10b and 4.15a indicate the location of Site #7 which was not in the main depositional zone but, rather, was situated in a channel that truncated two large ridges. The channel that contained this site contained exposed bedrock and was perched above the floor of Hattie Lake.

Figure 4.15: (a) Stereogram showing the elevation relationships between sites in the central part of the KGC. Note the ridges that Site #8 were cut into and the locations of (b) and (c). R denotes the large ridges composed of well-sorted sands. See Figure 4.10. (b) View eastward on the middle lobe. Gravel pit on far right is immediately north of Site #8. Note the undulatory profile across the ridges. (c) View SE from Site #10 indicating the ridged morphology of the KGC. These ridges continue to the location of Site #11.

The base of this channel is very diffuse and in places hummocky. On the north side of the channel hummocky terrain occupied higher ground and had an obvious trend perpendicular to the channel and parallel to the larger ridges. This site was located on the eastern end of a small ridge that trended west-east. These hummocks were composed of diamicton and many were mantled with boulder lags or thin bouldery gravel.

The limited exposure was dominated by cross-bedded sands and gravels interspersed with some planar sets. The upper unit of gravel was matrix-supported. Clast orientation was commonly chaotic but in some places there was crude bedding. Generally, the bedding conformed to the shape of the surface. Lower units of gravel were planar-bedded and contained larger imbricate clasts. Individual units were typically 1-2 m thick, with the sandy units being significantly thinner. One lens-shaped unit of cross-laminated sands was present and had conformable lower contact and an erosional upper contact. Several gravel clasts exceeded 0.75 m in diameter. Paleocurrent estimates indicated formative flow was parallel to the channel, toward the east-southeast.

At the contact between the small ridge and the glaciofluvial sediments was a deformed laminated unit that was bounded on the top and bottom by glaciofluvial sediments (Figure 4.16). The gravels were imbricate and often deformed into the laminated unit. Boulders up to 1 m in diameter were included. Clasts that were within 0.1 m of the laminated unit were aligned roughly parallel to the finer grained unit. The contacts between the gravels and the laminated unit were unconformable. The laminations within the unit were deformed and it contained sorted, coarse sands. In places, the laminations were nearly vertical and sometimes attenuated parallel to the contact with the gravels.

Site #8

Site #8 was located on the southeast-southwest sloping surface, bounded by the large ridges to the west and lower ridges to the north (Figures 4.15a and b). The large ridges to the west were composed of well-sorted sands and rose 8-10 m above the exposures at Site #8. At this site, the surface of the KGC was characterized by arcuate ridges that curved from the northeast to the west-southwest (Figure 4.15a and b). The excavation occupied the trough between two ridges and stopped at the high point of one of the ridges (Figures 4.15 and 4.17). At this location the ridges were closely spaced. The quality of the exposures was poor with only the upper 3-4 m exposed.

The general attitude of the bedding at this site is indicated in Figure 4.17. The geometry of the units in the northern faces was dominated by large-scale, planar beds, dipping toward the northwest (Figure 4.17a). The bounding surfaces were generally planar, but the dip of the beds

Figure 4.16: Deformed, laminated silts and sands at Site #7. The laminations were often attenuated and nearly vertical. This unit is bounded by erosional contacts. The gravels were deformed to conform to the shape of the laminated unit. Note the rounded boulder, found adjacent to the laminated sediments. Scale had decimetre divisions.

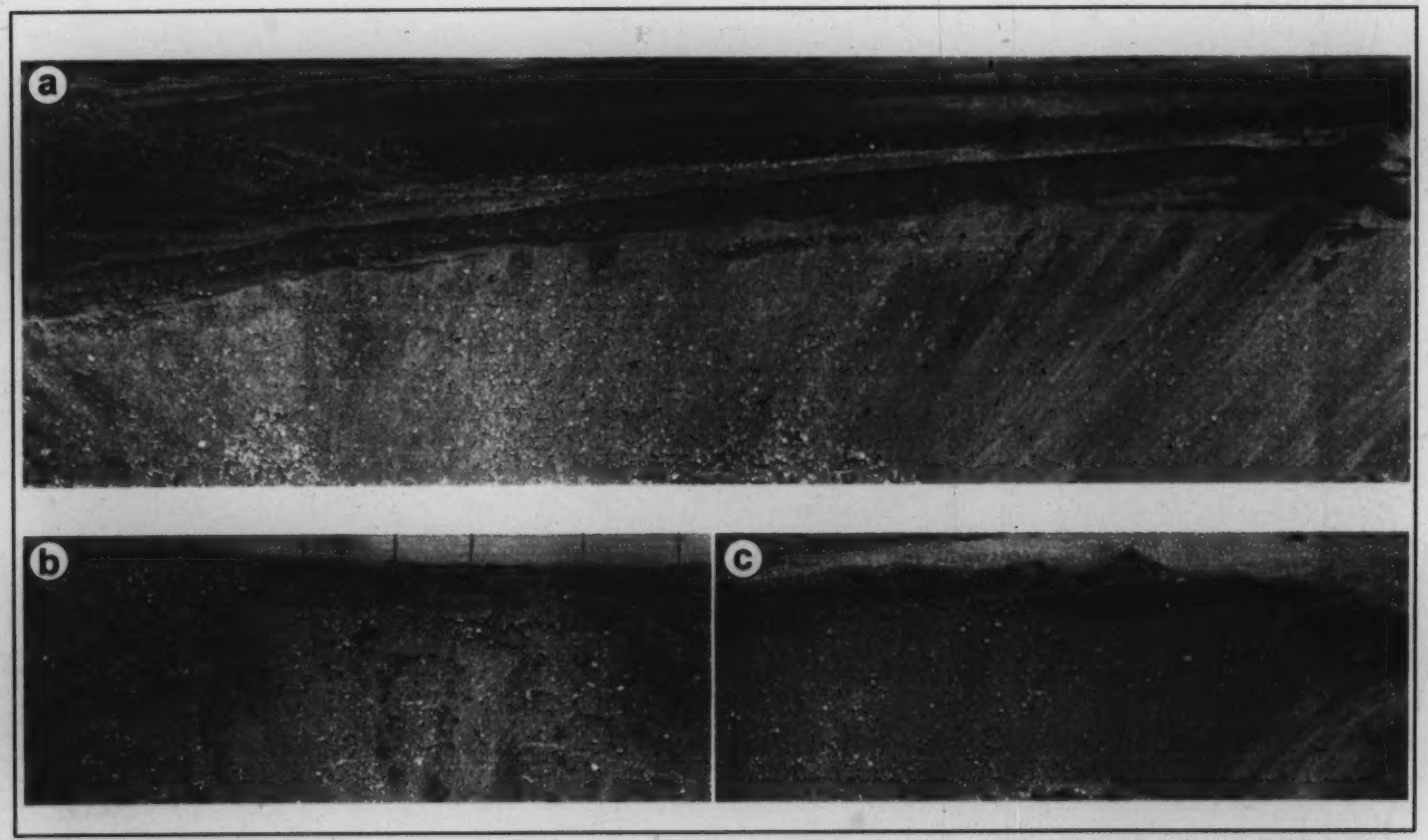

Figure 4.17: Sediments at Site #8. (a) This exposure cuts into one of the ridges shown in Figure 4.15b. The bedding dips to the NW and was dominated by large-scale, planar beds. The bedding is parallel to the slope of the landform. The other faces in this exposure were cut roughly parallel to the crest of the ridge and had roughly horizontal bedding. (b) Orientation of this exposure is parallel to that in (a). This location is on the SE side of the ridge that is located NW of that in (a). (c) Bedding on the southern side of this pit (immediately adjacent to the channel that contains Site #7) was associated with flow deflecting around the south side of the ridge.

varied. The contacts between different units were almost always erosional, with lags of coarser material present along the bounding surfaces. Such surfaces were occasionally curved near the top of the sequence. Where this occurred, the surfaces closely paralleled the undulatory crestline of the ridge. Conversely, concave-up bounding surfaces were associated with depressions in the ridge. Along the southern part of this site the orientation of the bounding surfaces was more variable than further north. Curved bounding surfaces were more common and associated with cross-bedded sands and gravels. In the south, units dip to the northeast to east. The southern part of the site is immediately adjacent to the middle channel that truncated the large ridge and contained Site #7. The interridge trough, in which the pit was situated, sloped to the south, paralleling the large ridge to the west (R in Figure 4.15a). The large-scale cross-bedding indicated that flow from the southern channel delivered sediment onto the middle lobe (Figure 4.17c). Sometimes the sediment in these southern units was composed of cobbles or large gravel-sized clasts suspended in planar- or cross-bedded sands.

Individual units were usually about 1 m thick, although lower units of imbricate gravels were up to 2-3 m thick. Generally, the sediments were composed of planar-bedded sands to cobble gravels with some boulders. The sediments were planar-bedded and imbrication was well-developed. The gravel units were nearly always clast-supported and imbricate to the bedding planes, indicating paleoflows up the bounding surfaces (*cf.*, Figures 4.15 and 4.17a). Sand units were usually planar-bedded though a few did possess cross-bedding that onlapped the bounding surfaces. Intraclasts of laminated sediments were present in some units. These intraclasts were more or less identical to the laminated sediments found at Site #6. The proximity of these two sites means it is probable that they had similar sources. The southern part of the pit had a larger component of sand-dominated units, though there were some bouldery units.

The sediments at this site indicated interfering flows converging from around the large ridge to the west. The ridge morphology on the glaciofluvial sediments became more chaotic (aligned hummocks) toward the southwest which is concurrent with the change in the bedding attitude. There was no evidence of a hiatus in deposition. The change in the morphologic expression, and the change in sedimentary architecture, indicate that there was a southwesterly shift in sediment source; from sediment deposited by flows coming from the northwest to those that were partly influenced by flow from the southwest (around the ridge). The textural change from coarser sediment to dominantly sandy sediment supports this interpretation.

Site #9

This site was located at the southeast end of the middle lobe of the KGC, immediately downflow from Site #8. It was situated at the confluence of the channels that delineate the lobe (Figures 4.10b and 4.15a). The surface of this part of the lobe had only minor surface relief. There were many small excavations northeast of this site that were dominated by clast-supported cobble gravels with a large component of sandy matrix. These small excavations were in very poor condition. Site #9 was immediately adjacent to Vernon Lake where bedrock was exposed at the surface and was overlain by a pervasive boulder lag.

The sediments exposed at this site are indicated in Figure 4.18. Nearly the entire exposure is composed of large-scale, tabular cross-bedded sands (Figure 4.18a). Planar- and cross-bedded gravels unconformably overlaid this sand-dominated exposure. The gravels were up to 1 m thick and formed a wedge-shaped unit that thickened to the southeast. Toward the southeast, the gravels were interdigitated with the sand units. Trough cross-bedded sands typically overlaid these gravels. The bounding surfaces between the different units were curved, irregular, or planar. Irregular erosional contacts existed between the cross-bedded sands and gravels near the top of the section. Most of the lower unit is trough cross-bedded. The lower tabular cross-bedded sand unit varied from 4 to 5 m thick. The gravels were of variable thicknesses but usually up to 1-2 m. The upper trough cross-bedded unit was approximately 3 m thick and composed of sand and gravel beds. The upper cross-bedded gravels were up to 1.5 m thick, though the excavation made it difficult to determine if it was continuous.

The lower tabular sand cross-beds were often normally graded with the base of each bed composed of pebbles. These sands were very well-sorted, though in places some coarser clasts were interspersed. The bedding planes were nearly always planar, but in one location cross-lamination was present. Some lens-shaped units, composed of well-sorted sands with faint bedding, were present. Toward the southeast, curved bounding surfaces associated with cross-bedded sands and gravels became more common. Clast-supported cross-bedded gravels and gravelly sands were both interdigitated with, and laterally continuous with cross-bedded sands to the southeast of the section (Figure 4.18b). These gravels were usually cross-bedded with minor planar-bedding. Boulders up to 0.75 m in diameter were present, but not common. It appeared that a cross-bedded unit of gravel had capped the entire section prior to excavation.

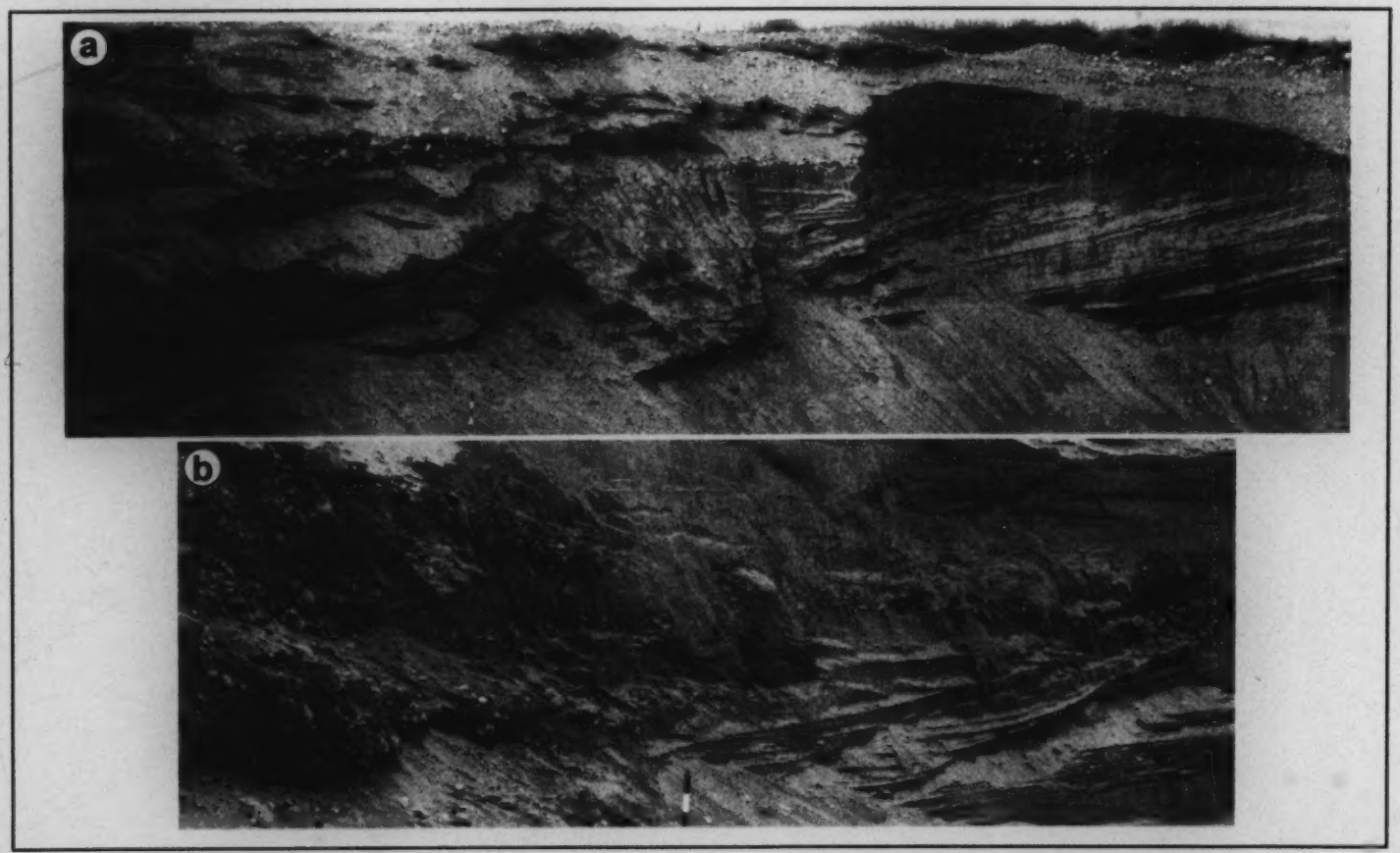

Figure 4.18: Sediments at Site #9. (a) This site was dominated by large-scale, cross-bedded sands near the bottom of the section. This sand facies was unconformably overlain by cross-bedded gravels and sands. This upper unit is primarily trough cross-bedded. (b) Well-sorted sands graded laterally into matrix-supported, chaotic gravels. This unit is overlain by cross-bedded sands and gravels. Scales have decimetre divisions.

Site #10

This site was situated on the southern lobe of the KGC (Figures 4.10b and 4.15a). At this location the surface was hummocky with minor, discontinuous channel forms. The hummocks were aligned in arcuate ridges that curved from the northeast to the west. The site had two separate exposures; the lower exposure was situated on the north slope of the southern lobe, and the upper exposure was situated on one of the highest points in the KGC (Figure 4.15a). The lower exposure was located immediately adjacent to the channel that contained Site #7 and separated the middle and southern lobes. This exposure was oriented roughly east-west and faced north (Figure 4.15a). The upper pit was situated among the arcuate ridges and swales that characterized the surface of the southern lobe. Most of the exposures in the upper part were obscured by colluvium, though one west-facing exposure will be described.

Sediments in the lower pit were dominated by laterally-continuous units of cross-bedded gravels and sands (Figure 4.19a). The bounding surfaces were primarily erosional with the only gradational contacts between sand and gravel units near the top of the sequence (Figure 4.19b). It was common to find the upper contacts of one unit lined with small, imbricate boulders, armoring the underlying sediments. The bounding surfaces were generally planar on the scale of the exposure but there were several examples of undulatory and curved contacts. Such surfaces generally dipped toward 170-190°. Curved bounding surfaces were usually filled with cross-bedded sands or at least finer-grained sediment than the enclosing sediment. Some bounding surfaces were convex-up with clasts aligned parallel with the contacts. Curved bounding surfaces were more common in the upper part of the sequence. The texture of the sediments varied widely from bouldery gravel to well-sorted sands, with one occurrence of cross-laminated sands.

The geometry of the units appeared to be linked to the surface morphology. The dip of the units was toward the south which was roughly perpendicular to the arcuate surface ridges. Discontinuities in the ridges appeared to be recorded in the sediments in the form of oblique erosional surfaces. Some lens-shaped units of sand were present. Generally, the geometry was of dipping units of relatively uniform thicknesses. These units were planar- or sheet-like, although there were some that pinched out laterally and formed gently tapering wedges. Most of the units were approximately 0.5-1 m thick. There was a tendency for the lower units to be relatively thick. The units were laterally extensive and could be traced for tens of metres.

The exposure was dominated by clast-supported gravels and bedded sands but within one unit the texture often changed laterally (Figure 4.19b). Matrix-supported gravels were not common

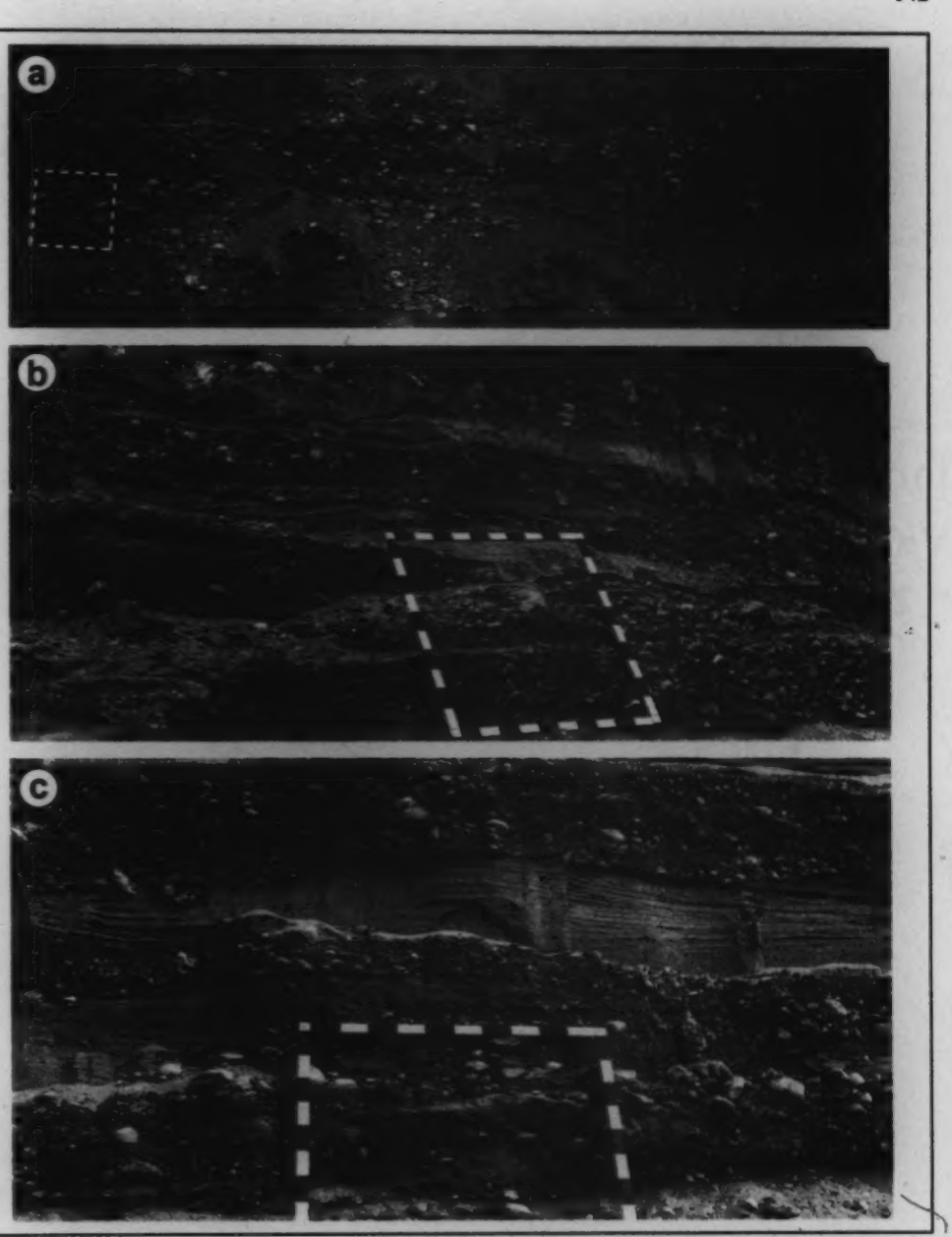

Figure 4.19: Sediments at Site #10. (a) Sediments at the base of the lower pit were dominated by laterally-continuous units of cross-bedded gravels. (b) Near the top of the lower pit the bounding surfaces were often undulatory, with a greater component of sand than lower in the pit. (c) The limited exposures in the upper pit were dominated by interbedded sand and gravels units. These units were planar- and cross-bedded and some units had gradational contacts. The scales had decimetre divisions.

but were present in some locations near the base of the pit. This matrix-support in places changed laterally to clast-supported gravels. The cross-bedded gravels often graded laterally into cross-bedded sands which, in intermediate steps, had pebbles lining individual beds. In some locations, openwork gravels graded laterally to sands. Cross-beds were usually tabular but some of the finer units were trough cross-bedded. Larger clasts were usually parallel or slightly imbricate to the bedding planes. Rotated clasts were common and cobble clusters were present in some normally-graded units. Paleocurrents were estimated from cross-bedded units and indicated flow toward the southeast and south. Bounding surfaces generally dipped to the southeast and south. The morphology of the surface ridges trends from the west-southwest to the east-northeast. Therefore, the sedimentary architecture and the surface morphology indicated paleoflow toward the south-southeast or southeast.

The sediments of the upper part of this site were very similar to those found in the lower part. Here a sequence of curving bounding surfaces was present (Figure 4.19c). Planar-bedded sands were unconformably sandwiched between imbricate, planar-bedded gravels. Cluster bedforms were also present and there were rapid lateral changes in the texture of the units.

Site # 11

This site was located along the southern edge of the southern lobe of the KGC (Figure 4.20). The southern margin was curved and sloped steeply to the adjacent hummock-bottomed channel. It was located directly south-southeast of Site 10. This area had been extensively excavated for aggregate. To the east an arm of Vernon Lake was mantled with an extensive boulder lag and was saline. To the south, hummocks within the channel, were composed of heterogeneous gravels and large boulders that possessed no discernible bedding. Immediately to the west, hummocks composed of diamicton were indistinguishable from the gravel hummocks. A large, southward-sloping trough defined the eastern edge of the pit (Figures 4.20 and 4.21). This trough was paired with a more easterly oriented trough that passed between Site #12 and 13. This site was situated slightly lower than Site #10 (upper part) on a surface that contained ridges and troughs on the surface. These ridges were southern extensions of ridges at Site #10. The surface morphology was undulatory, with 1-1.5 m of relief in the western part of the site, and a ridge wavelength of approximately 75-100 m. West of the exposure, the ridges curved to the west-northwest. They were discontinuous, with breaches aligned nearly perpendicular to the ridges. In the eastern part of the site the surface topography was characterized by more chaotic bumps that were 25-50 m across and less than 1 m high. There was

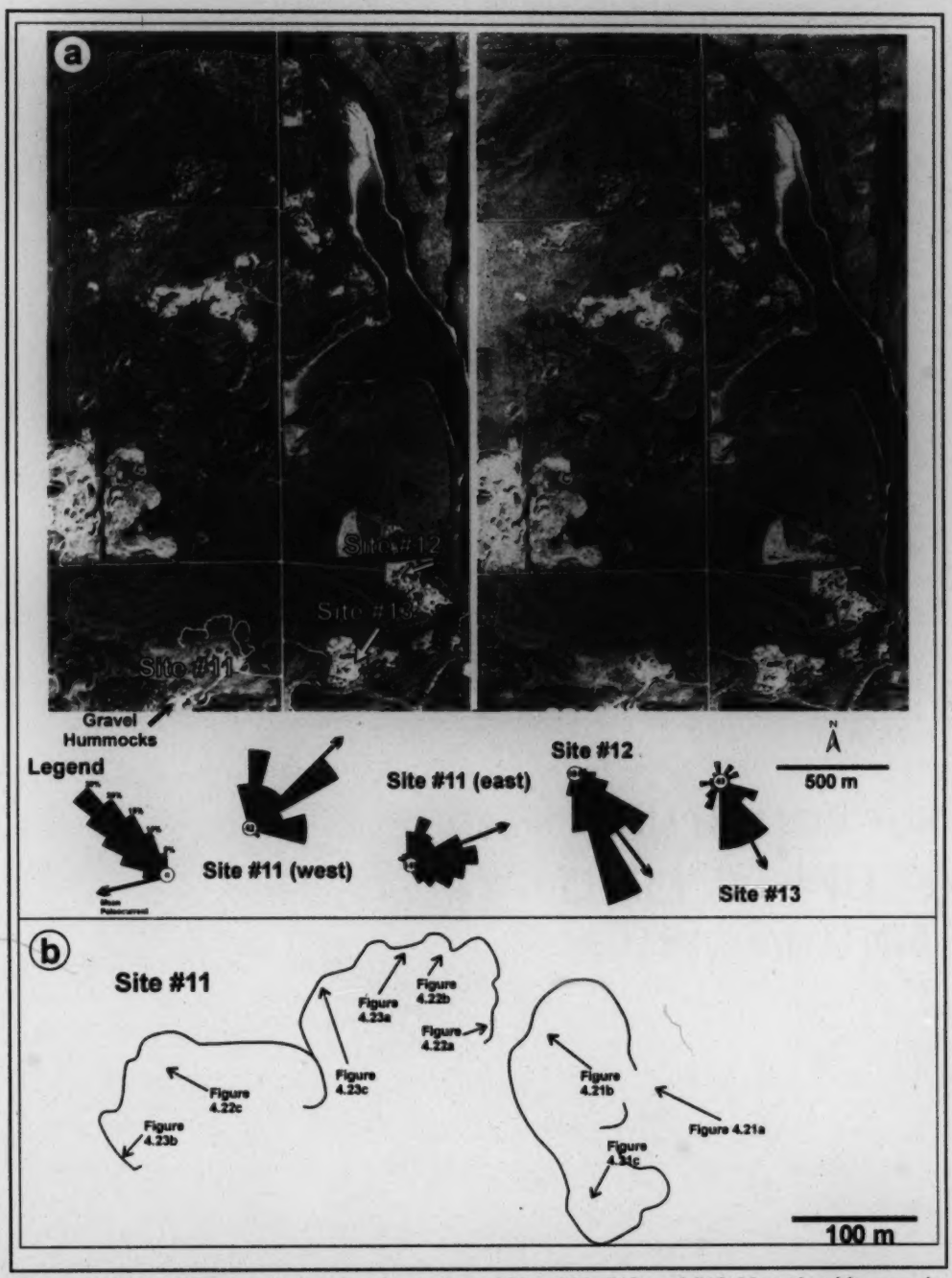

Figure 4.20: (a) Stereogram showing the setting of Sites #11, #12, and #13. Note the ridges on the surface of the KGC at these locations. Paleocurrents from these pits are described in the text. (b) Close-up of Site #11 indicating the pit faces shown in Figures 4.21, 4.22 and 4.23.

Figure 4.21: Sediments at Site #11. Refer to Figure 4.20 for locations. (a) View toward the NW showing the correspondence between the surface morphology and the bedding found in the eastern pit. Note that the exposure was cut into the SE side of a sloping landform. (b) Close-up of the pit faces in (a). Note that the bedding was dominantly planar-bedded gravels and sands with secondary cross-bedded gravels (base of section). (c) Steeper beds on the southern extent of the pit. In the lower right portion there are cross-laminated sands that were often found as rip-ups in the overlying gravels.

a hierarchy of elements at this scale and larger (Figure 4.20).

The bounding surfaces were always erosional with dramatic changes in the dip angle between units. The surfaces were nearly always planar and dipped at low angles and very closely paralleled the surface topography (Figure 4.21a and b). These beds were dominated by clast-supported gravel with secondary planar sands (limited cross-bedding was observed). Individual units were commonly less than 2 m thick but one unit of clast-supported, planar-bedded gravels was nearly 3 m thick. Units were laterally extensive, often traceable for up to 30 m. Where the bounding surfaces were curved and channel-like, the scour was infilled with cross-bedded sands (this was rare). In locations where coarse sands or gravels overlaid laminated sand, there were intraclasts of the finer material near the base of the coarser unit.

The composition of this pit was dominated by clast-supported gravels that were generally sorted. Where gravels were planar-bedded, the clasts had obvious imbrication that indicated flow down the foresets (Figure 4.21c). Some rotated clasts were present on the foresets and minor slumping had disturbed the bedding in some of the beds. Minor units of cross-bedded gravels were interspersed within the dominantly planar-bedded exposures. These cross-beds indicated paleocurrents consistently toward the east and southeast. Cross-bedded units were also clast-supported. Units of planar-bedded sands were commonly interbedded with the cobble gravels and occasionally constituted a significant portion of the section, particularly in the trough that defined the margin of the excavation. Usually they comprised a smaller proportion of the exposures bounded by cobble gravels. Often there were minor, lens-shaped units of planar sand that had mantled the underlying gravels. Ripple-drift cross-laminated sands were present in the section but made up a very small proportion of the exposures (Figure 4.21c). Intraclasts composed of this cross-laminated material were often present in the overlying gravels. The cross-bedding indicated flow down the dipping bounding surfaces without any indication of reversed currents. Therefore, this pit is interpreted as an accreting macroform with superimposed dunes.

In the western part of this site, exposures cross-cut the area at several different angles so the relationship between the surface morphology and sediments was more apparent (Figure 4.22). The bounding surfaces were nearly always erosional. Abrupt changes in texture were common. Bounding surfaces were undulatory and roughly parallel to the surface morphology in many places, although some cross-cutting did occur (Figure 4.22a). Smaller-scale bounding surfaces defined scours, or dish-shaped units, that were associated with truncation of underlying sands and often filled with cross-bedded sands or gravels. These undulatory units were secondary to those in inclined sheets. These

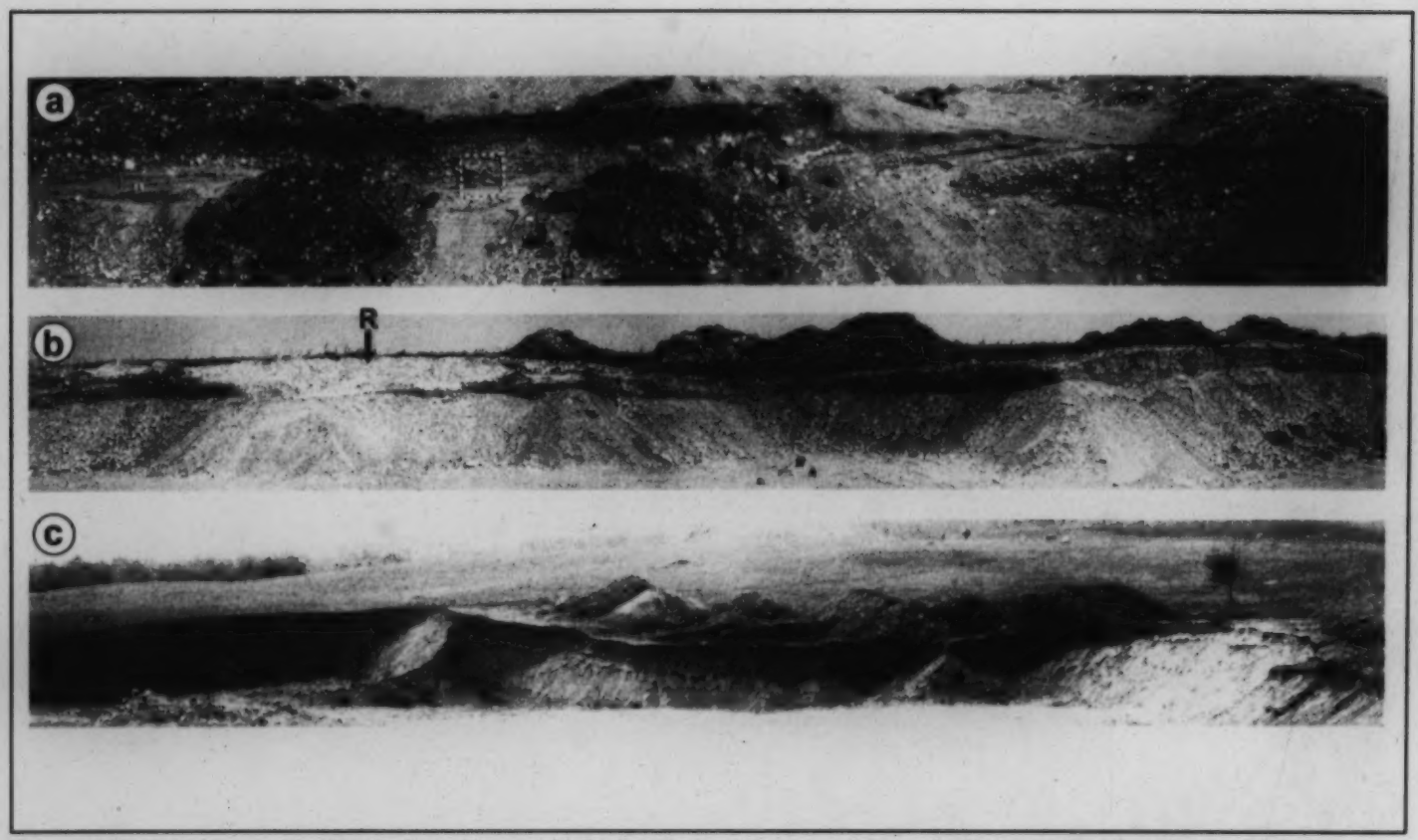

Figure 4.22: Sediments at Site #11. Refer to Figure 4.20 for locations. (a) Large-scale cross-bedded gravels and sands. Note that the attitudes of the beds opposed each other. (b) On the left side of this figure, note the planar-bedded units and how they conformed to the surface morphology. The bedding dipped away from R which was the crest of one of the ridges indicated on Figures 4.15a , c, and 4.20. (c) View to the NW. Note how the bedding attitude conforms to the shape of the surface. These surface features were immediately SE of the ridges indicated in Figure 4.15c. Scales have decimetre divisions.

sheets maintained their thicknesses laterally (Figure 4.22b). The units were usually less than 1 m thick with sand units being thinner. Paleocurrents were determined to be both up and down these inclined units. Cross-bedding in the gravels was primarily tabular and downlapped or onlapped the bounding surfaces. Paleocurrents in the sand units were relatively erratic. Paleocurrents were determined from imbricate units and primarily from cross-bedded units. These planar, dipping units were laterally continuous for up to 30 m.

The internal geometry of individual units changed dramatically between units. Gravels were nearly always clast-supported with occasional matrix-supported units (Figure 4.23). Pods of matrix-supported units were found suspended in sandy units. Planar-bedded units were the most common; this was the case with both sand-dominated and gravel/boulder-dominated units. Cross-bedding was found in both coarse and fine-grained sediments. Gravel-dominated units were usually tabular cross-bedded, whereas the sand-dominated units also exhibited trough cross-bedding. At a few locations vertical changes from gravel to sands (and in some places, fine sand with cross-laminations) was rhythmic (Figure 4.23c). Where present, ripple-drift cross-lamination alternated between Types A, B, and S and therefore indicated rapid fluctuations between sedimentation and transport (Figure 4.23c). The upper contacts of these units were erosional and the lower contacts in places draped the gravel and, in one location, small faults were found. Graded sand units were not common and where present were not extensive. Faulting was very uncommon in the exposures, but where present about 1 cm of displacement was observed.

Site #12

This site was located along the eastern edge of the southern lobe of the KGC (Figure 4.20). The lobe trended northwest-southeast and was flanked on the east by Vernon Lake. To the north a trough/channel branched off and separated the two main components of the KGC. This trough/channel was broad and sloped gently in the vicinity of Site #12. On the southwestern and southern edge of the lobe were troughs that curved around and were confluent with Vernon Lake. These troughs were elongate depressions that had undulatory long profiles. The upper surface of this lobe was gently undulatory with broad, low-relief elements that were visible mainly because of vegetation enhancement (Figure 4.20). Across Vernon Lake to the east, hummocky terrain was at a lower elevation than the sediments at this site. An esker directly south of this site and Site #13 was significantly lower than the sediments in these pits and was demonstrably subglacial, because of the undulatory long profile of the crestline. Southeast of this site, Vernon Lake defined the main outlet

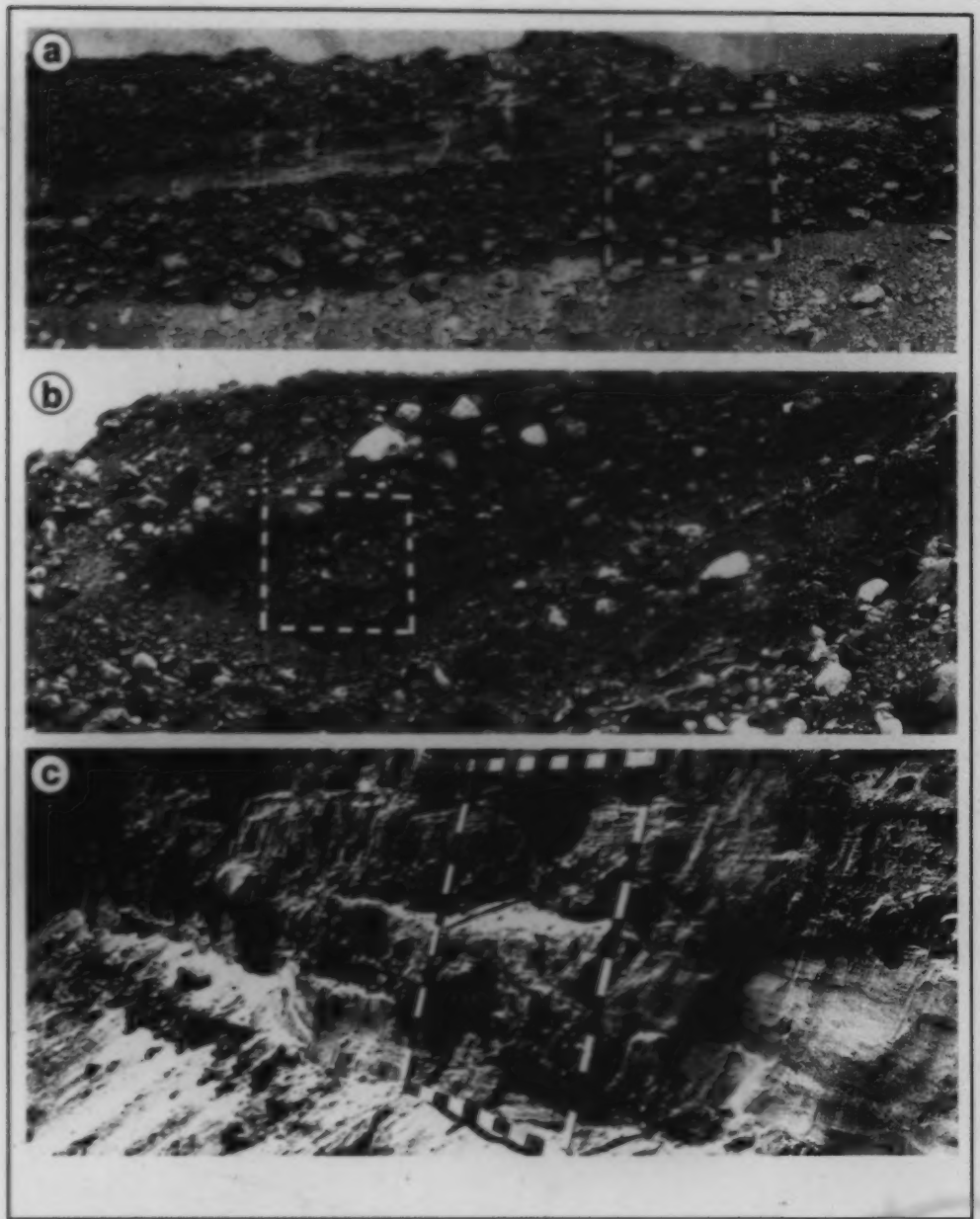

Figure 4.23: Sediments at Site #11. Refer to Figure 4.20 for locations. (a) Vaguely-bedded gravel and cross-bedded sand. Many of the units were poorly sorted. The attitude of these beds was parallel to the surface slope (this area is indicated on the left side of Figure 4.22b). (b) Steeply dipping beds of clast-supported cobbles/boulders. This location was within 25 m of the gravel hummocks immediately south of the pit. (c) Interbedded gravels and cross-laminated sands. Scales have decimetre divisions.

to the KGC and eventually was confluent with the Battle River between Irma and Wainwright.

Bounding surfaces were always erosional and curved. They had very low curvature and in places appeared almost planar, particularly in the upper portions of the exposure. Lower in the exposure the curvature was greater and the units thicker with larger cross-beds. The erosional bounding surfaces were nearly always defined by a lag of cobbles. The lower bounding surfaces were curved and usually concave-up. Often the upper surfaces of these units were also concave-up and out of phase with the lower bounding surfaces. The units in the upper portion of the exposures were relatively thin, seldom greater than 1 m (Figure 4.24). Units in the lower portion were usually thicker, often greater than 1 m. The lateral extent of the units was in the range of tens of metres. Paleocurrents were toward the southeast (toward the outlet defined by Vernon Lake).

The units were dominated by gravels and sands. The gravels were nearly always clast-supported. No rhythmicity was apparent in the alternation of the units. There was no apparent trend to the thickness or extent of sand or gravel units. Sand units were often well-sorted with larger (gravel-sized) clasts dispersed throughout. This indicated that the flow was capable of transporting larger clasts but their supply was limited. Bimodal gravels/sands were present in many cross-beds. Trough cross-bedding in both sand and gravel units was common. Some cross-bedded units were well-sorted, whereas others were polymodal (determined visually). Cross-beds were often normally-graded, with openwork pebbles to sand (Figure 4.24b). Ripple-drift, cross-lamination was present but not common (Figure 4.24c).

Site #13

This site was located on the southeast corner of the southern lobe of the KGC (Figure 4.20). The lobe was defined on the north by the connected troughs that separated this lobe from the one that contained Site #12. The sediment in these troughs was dominated by larger clasts than found in the lobes themselves. The sediment was more chaotic and indicated a highly turbulent environment. The southern margin was defined by a west-east oriented channel that also defined the southern extent of Site #11. The eastern and southern margins were defined by the channels, occupied by Vernon Lake where boulder lags were pervasive.

Two pits will be described at this site. The western pit was dominated by large-scale cross-bedding which was rhythmically bedded. The majority of the sediment was composed of sand and gravel. Planar sand units dominated, with a secondary component of gravel. The finest fraction was fine sand that draped larger clasts. In gravel units, clasts larger than sand were clast-supported and

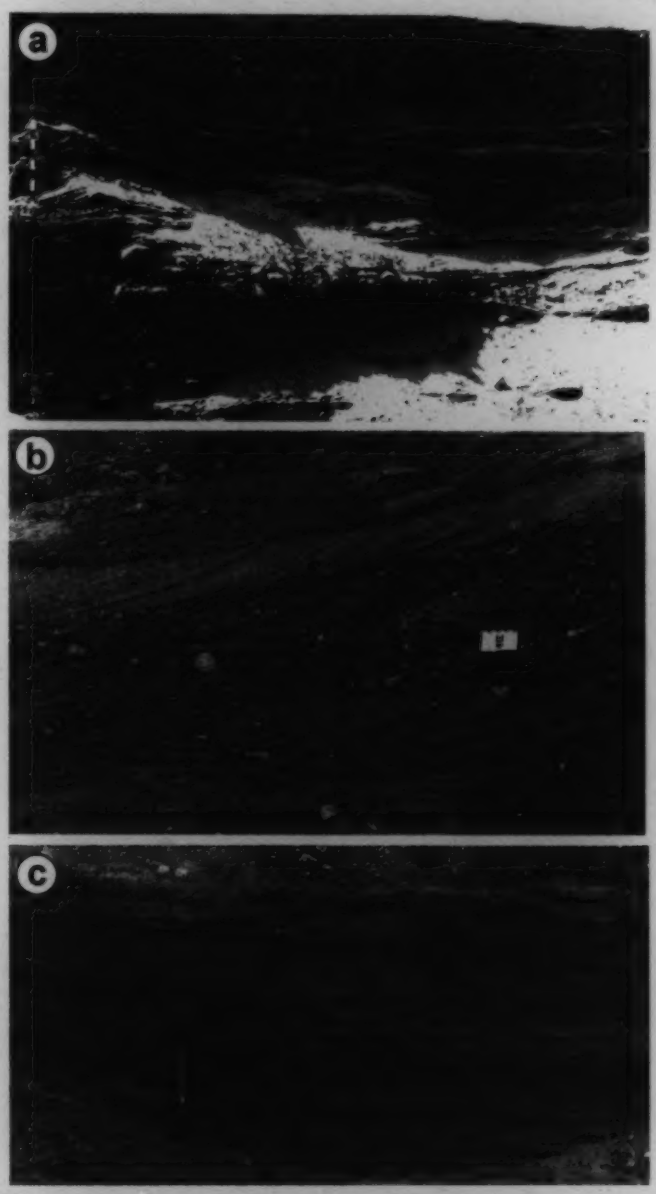

Figure 4.24: Sediments at Site #12. (a) This site was dominated by cross-bedded sands and gravels. The units were usually less than 1 m thick and had curved bounding surfaces. Scale had decimetre divisions. (b) Individual units often had lateral changes in texture. Lags were common at erosional contacts. (c) Cross-laminated sands were not common but one limited example was interbedded with gravels and sands.

some beds were openwork. The upper bounding surface of the large-scale cross-bedding was erosional and overlain by heterogeneous gravels. The lower contact was not exposed at this site but bedrock was exposed about 50 m to the south of the section and was 1-2 m lower than the base of the exposure indicated in Figure 4.25. This cross-bedded unit was at least 4 m thick and was laterally continuous for the width of the excavation. Angle of the foresets changed slightly over the exposed face but this was easily explained by adjustment of the crest of an accreting bedform. The sediments contained were usually planar-bedded and parallel to the bedding planes. Not all of the beds were of equal thickness along their length but the majority were of consistent thickness. Clasts in gravel units were usually parallel or imbricate to the bedding planes, but some larger clasts showed rotation. Pebbles were often found suspended in a sandy matrix.

The eastern pit was composed of steeply dipping beds of gravels that roughly paralleled the shape of the landform. Within some gravel beds, poorly-sorted and crudely reversed grading was present. The beds were usually rhythmically bedded with each being normally graded. Fine sand beds often draped underlying pebbles and were unconformably overlain by gravels. Some minor faults were present, indicating displacement of approximately 1-1.5 cm. The orientation of these faults indicate that they were probably due to the excavation.

Sediments of the Main Outlet Channel

Site #14

This site was part of a point bar-like landform with a hummocky surface along the inner portions. This bar was truncated on the inside of the bend by a 'stream trench' (*cf.*, Chapter Three). The surface of the landform sloped gently to the north. The northern parts of the site were elevated above the interfluves but the inner (northern) part was inset well into the bedrock valley that was occupied on the northern side by Vernon Lake. Bedrock was exposed along the northern margin and was also exposed in the 'stream trench' that truncated the landform to the south. The main channel curves to the north and then to the south on its way to Irma (Figure 4.2).

The sediments were not exposed well in the point bar but, where visible, were composed of fairly well-sorted gravels. These beds were almost always planar-bedded (Figure 4.26a). Bedding planes were commonly continuous for the width of the exposure and typically dipped to the north at a higher angle than the surface of the deposit. Clasts up to 2 m in diameter were present at the base of the deposit but generally the area was dominated by pebble and cobble-sized material with a significant component of sand in planar-bedded units. As with the gravels, the sands were in thin

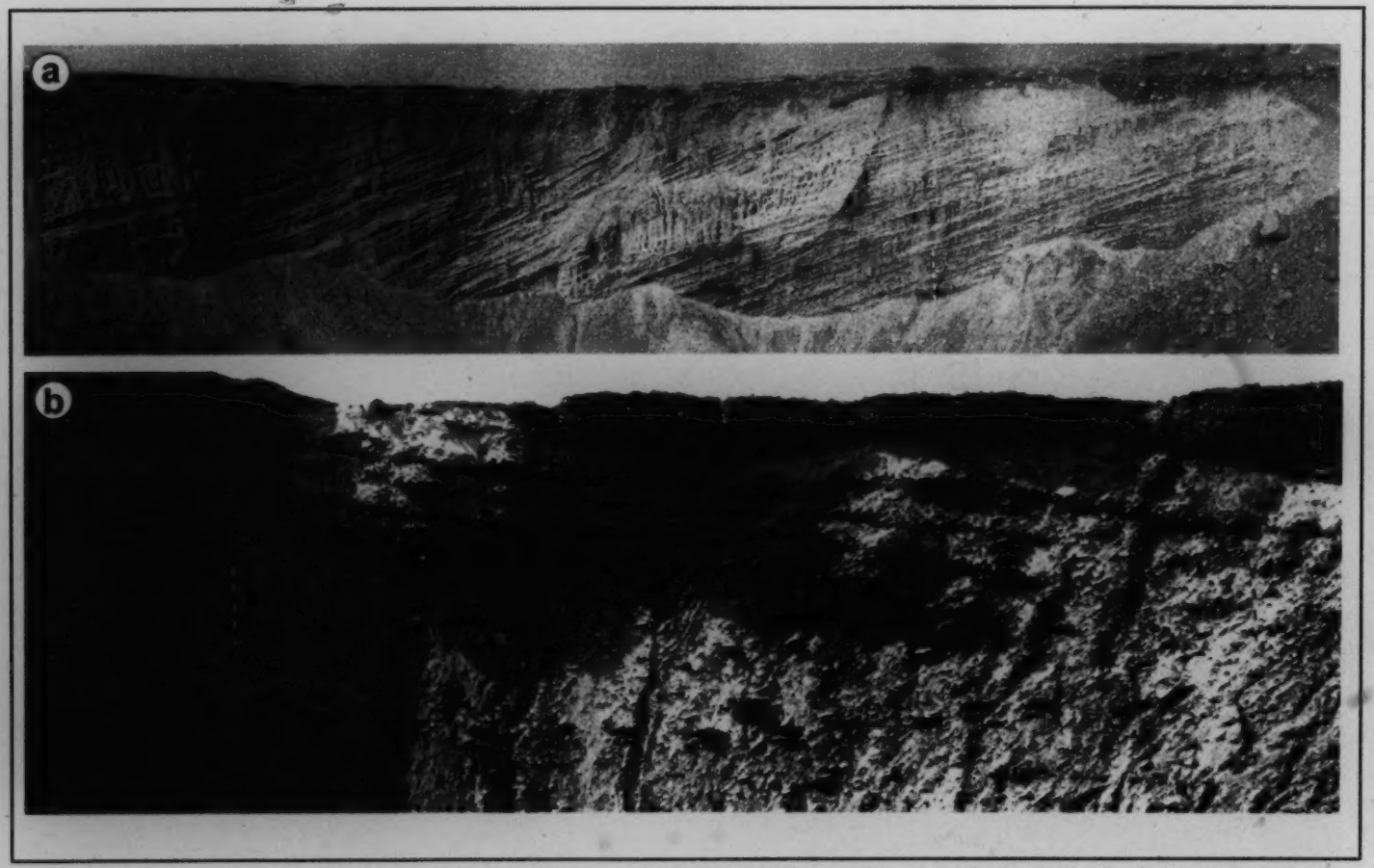

Figure 4.25: Sediments at Site #13. (a) Large-scale tabular cross-bedded units. These sediments were dominated by rhythmically bedded sands and gravels. Sands dominate, with a secondary component of gravel. (b) Sediments in the eastern pit had the same architecture as the western pit but were dominated by gravels. Scales have decimetre divisions.

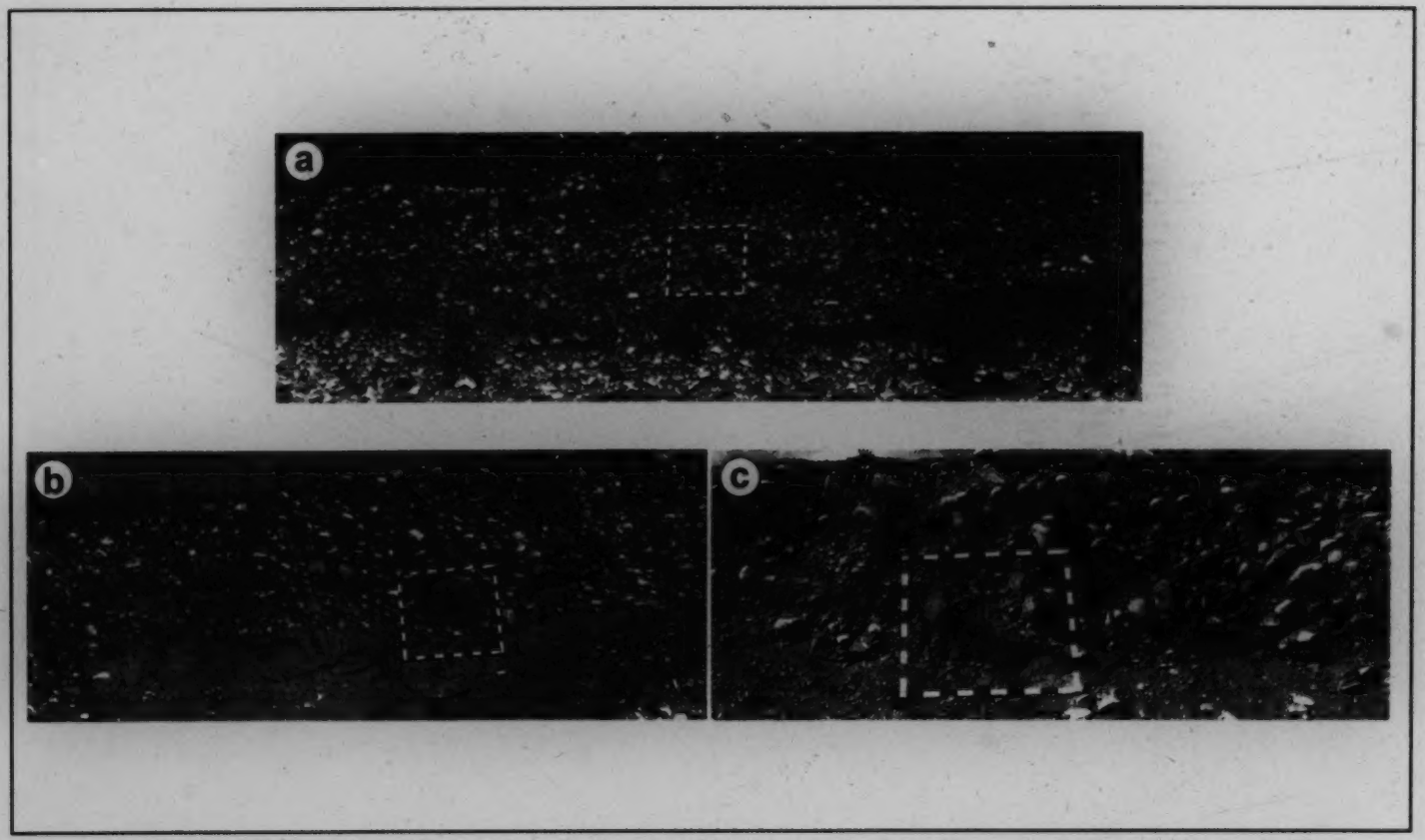

Figure 4.26: Sediments in the main outlet channel. (a) Sediments at Site #14 were dominated by gently-dipping cobble gravels. These sediments were part of a point-bar-like landform that sloped toward Vernon Lake to the north. (b) Sediments at Site #15 were composed of cobble gravel and boulders. These sediments were typically planar-bedded. (c) Sediments at Site #16 were more chaotic than Site #15 with some cross-bedded units. The sediments were more texturally variable also. Scales have decimetre divisions.

beds that dipped to the north. Bedrock was exposed in the deeper pits.

Site #15 and #16

Both sites were located on a narrow septum between two channels. The northern channel was continuous with the main outlet from the KGC and the second was connected to the anabranching system of channels that were a continuation of the main 'stream trenches' (Figure 4.2). At this narrow septum the two channels diverted around a higher area and then curved southwards at Irma. Glaciofluvial sediment was widespread in this area and was found on the point bar south of Irma, on the narrow septum mentioned above, and was particularly pervasive southeast of the large ridge that diverts the channels toward Irma. Sediments southeast of this ridge were composed of gravels and coarse sands. These sediments provide a nearly continuous glaciofluvial mantle between this ridge and the Battle River. The sediments were presumably the proximal equivalent to the sediments south of Wainwright (Shetsen 1990).

Sediments at Site #15 were composed of cobble-gravel that was nearly always clast-supported. Clasts are rounded to subrounded. There is a crude coarsening upwards and the sediments were dominated by planar-bedded units with a few cross-bedded units (Figure 4.26b). Openwork cobbles and pebbles were common.

Sediments at Site #16 were dominated by clast-supported, rounded gravels to boulders (Figure 4.26c). Boulders greater than 2 m in diameter were present and commonly striated. Cobbles and boulders were crudely imbricated in most locations, and openwork units were present. Cobble lags often separated finer cross-bedded units and the more heterogeneous, clast-supported units of coarser material above. In several locations, well-sorted, planar- and cross-bedded sands were unconformably overlain by the clast-supported, chaotic bouldery gravels. Some of the beds contained pebbly sands. Where cross-bedded gravels and sands were found, they were always overlain by chaotic boulder gravels. There were many occurrences of rafts of silty diamicton in the gravel units (Figure 4.26c). Normal faults were present but not common. Where present, displacement was less than 30 cm. Convoluted, bedded sands indicated that deformation occurred during/post deposition of the gravels.

Discussion

Summary

Several characteristics of the inlet channels are critical to the interpretation of the landforms and sediments of the KGC. First, the northern end of the trough that connects the KGC to the Birch Lake depression, and the Sedgwick district, contained one main channel that exhibited an appreciable amount of glaciofluvial sediment. It is important to note that this depression also contained erosional channels that approximately parallel the main inlet channel. Some of the channels did not occupy the trough but, rather, traveled up and over a bedrock controlled upland and exhibited convex-up long profiles (*cf.*, Chapter Three). All these channels converged on the KGC and, on the basis of perched glaciofluvial deposits on the interfluves, are inferred to have operated contemporaneously with the main inlet channel. Second, many of the channels that converged on the Lac Loranger depression, including the one that contained Sites #1 and 2, oppose the regional slope. The formative flows in these systems must have been pressurized. Third, in the northernmost extent of the main trough, eskers overlaid glaciofluvial sediments. Also, in the western inlet channel discontinuous eskers overlaid the sediments, shown to connect with the KGC. Fourth, glaciofluvial erosion and deposition truncated and onlapped the hummocky terrain. Fifth, bedding of the glaciofluvial sediments often conformed to the shape of hummocky landforms which indicated that they were primary landforms and not solely due to removal of lateral ice constraints. Sixth, the competence of these flows was significant enough to transport boulders up to 3 m in diameter. Seventh, after the deposition of the glaciofluvial sediments, slope processes, lacustrine deposition, and periglacial processes made minor modifications to the landforms.

The above lines of evidence are convergent on a very different genetic interpretation than has been suggested for this area (Gravenor and Bayrock 1956; Gravenor and Ellwood 1957; Bayrock 1957). The presence of eskers on top of glaciofluvial landforms (that often had concave-up long profiles) which, in turn, truncated hummocky terrain, indicates that all were formed subglacially. If the glaciofluvial system contributing water and sediment to the KGC was demonstrably subglacial it follows that the KGC formed in either a subglacial or ice marginal environment.

Four basic types of sediment are found in the KGC: laminated lacustrine sediments, subglacial diamicton, well-sorted sands in the large ridges (Figure 4.10), and coarser glaciofluvial sediments in the main part of the complex. Laminated lacustrine sediments were found in two locations in the KGC. The first location was at Site #6, Pit A. At this location the laminated sediments draped the underlying glaciofluvial sediment. This lower sediment is interpreted as

glaciofluvial on the basis of the presence of Canadian shield clasts. The laminated sediments were truncated and deformed at the top, and contained few clasts. Laminated lacustrine sediments were also found perched on the northern margin of the complex (Figure 4.10a). These sediments were highly deformed. The soft-sediment deformation structures indicated flowage. A discontinuous, diamicton capped the sequence. The exposures were in poor condition so little work was done at this location.

The diamicton is interpreted as subglacial till on the basis of the structure and the clast fabric (Figure 4.11) at a single exposure at Site #6. The lower contact of this diamicton was deformed into the underlying gravels. The structure of the lower part of this diamicton was massive, with indistinct horizontal structure. Near the top of the unit, relatively massive diamicton graded into faintly laminated sediment. The upper contact of this diamicton was always scalloped (Figure 4.13b). The clast fabric was analyzed using the eigenvalue method (Mark 1973; Woodcock 1977), and indicated an intermediate to strong orientation. The normalized eigenvalues were: S1=0.622, S2=0.243, S3=0.136, with a clustering of K=1.620. These values, when placed into context with other glacial sediments, indicate that this diamicton was likely formed by lodgement and/or ductile flow (Dowdswell and Sharpe 1986; Hicock et al. 1996). On the basis of the relatively massive deformed lower extents, and the faintly laminated upper portions, the diamict likely represents a transition between lodgement/meltout to a subglacial lacustrine environment. Diamicton was also found within hummocky terrain along the margins of the KGC as well as in the hummocks on the western side of the middle lobe. Diamicton along the eastern margin of Hattie Lake mantled bedrock and was capped by boulder lags and/or thin glaciofluvial sediments. Diamicton with faint laminations was also found intercalated with glaciofluvial sediments at Site #7.

The glaciofluvial sediments were found beneath and on top of the diamicton and lacustrine sediments. They were also found in the esker-like feature at Site #6 that clearly overlies and truncates the diamicton unit. At some locations glaciofluvial sediments were found mantling hummocky terrain and at others (Sites #1 and 2) the glaciofluvial sediments and hummocky terrain were formed contemporaneously. Glaciofluvial sediments often contained intraclasts of fine-grained diamicton and laminated sediments. These intraclasts were usually small (< 50 cm long) and enclosed in matrix-supported gravels or coarse sand units.

Glaciofluvial sands were present in the large ridges that dominate the topography of the KGC. The ridges were composed of well-sorted sands and overlaid the hummocky terrain. In addition these ridges had operated as obstacles to the flow that deposited the main bulk of the

sediment in the KGC. This contention is supported by the deflection of paleocurrents around the ridges and the orientation of the ridge/swale topography that dominates the middle lobe of the KGC. The tops of these ridges are roughly the same elevation as the perched lacustrine sediments on the sides of the KGC (Figure 4.10a). Thus, on the basis of the cross-cutting relationships and the stratigraphic information at Site #6, development of the large ridges and lacustrine sediments must have preceded the main depositional event that formed the KGC.

Interpretation

Several aspects of the morphology and sediments in the KGC indicate a complex developmental history. First, the north-south oriented, bedrock-controlled depression that contains the KGC would have acted as a natural collector of glacial meltwater; proglacially and subglacially. Second, the basin would have acted as a preferred location for deposition of lacustrine sediments (proglacial and subglacial) and till. Third, given that several authors (e.g., Bayrock 1955; Gravenor and Ellwood 1957; Young et al. 1994) and observations during the current study did not show evidence of multiple glaciations in this area, sediments in the KGC are interpreted as an interglacial-glacial-deglacial sequence. Consequently, the interpretation of the development of the KGC follows a logical progression.

Preglacial

The Viking upland developed as an erosional residual formed by the lateral planation and vertical incision of the Vermilion and Wainwright valley systems (*cf.*, Alden 1932; Warren 1939; Young 1991, 1996). At this time, depressions in the upland were accentuated by minor tributary streams. The incision of the north-south oriented trough, within which the main inlet channel and the KGC were located, occurred during that phase.

Glacial Onset

Glacial onset in this area was characterized by ice-frontal glaciotectonism along preglacial valleys and up-glacier facing escarpments. In addition, proglacial outwash was channeled down the depressions and lakes formed in internally-drained depressions. The glaciotectonism is recorded in hummocky terrain (Chapter Five). Proglacial outwash is recorded by the basal glaciofluvial sediments, below the diamict at Site #6. At this time proglacial channels flowed along the ice margin toward the southeast. These channels would later be modified into the 'stream trenches'. It should

be noted, however, that not all of the stream trenches would have originated in this manner. The stratigraphic, topographic, and sedimentologic characteristics of the channels requires that they were polygenetic (*cf.*, Chapter Three)

Early Subglacial

During the first part of the subglacial stage, debris entrainment and then deposition of the till occurred. Deposition of subglacial sediment took place both in depressions and on the higher parts of the Viking upland, though the amount of sedimentation was not sufficient to completely mask the underlying topography. Thus, the basin that contains the KGC existed subglacially. Deposition of this till involved deformation of the underlying outwash gravels, as at Site #6. Further deposition was accomplished by a combination of lodgement and meltout processes.

As the Laurentide ice sheet neared its maximum extent (*cf.*, Dyke and Prest 1987), the combination of thicker ice and geothermal heat caused subglacial lakes to form (Shoemaker 1991). The enclosed basins that were present on the Viking upland, including the basin that now contains the KGC, were ideal subglacial topographic settings for small subglacial lakes to form. The sediments associated with such lakes were recorded in the gradation between the diamicton and lacustrine sediment at Site #6, and the perched lacustrine sediments along the margins of the KGC. The large ridges in the KGC were deposited at this time as a quiescent phase of the cavity-filling event. Similar sequences of subglacial till and subglacial lacustrine sequences have been reported by Munro-Stasiuk (in press) in southern Alberta.

Middle Subglacial

Destabilization of the ice sheet, during deglaciation, caused the catastrophic drainage of subglacial lakes in several sectors of the Laurentide ice sheet (Shaw et al. 1996; Shaw et al. 1998). The drainage of these lakes likely occurred in a domino-like fashion, not unlike that proposed for proglacial lake drainage (Clayton 1983). These catastrophic releases had immense geomorphic impacts in the main flood paths (Rains et al. 1993; Shaw et al. 1996; Sjogren et al. in review) but on the higher intervening zones only minor erosion would have occurred. During this catastrophic release, water overtopped the Viking upland for a short time as sheetflow. As discharge waned, flows rapidly channelized.

This partly channelized flow overtopped the high points of the terrain forming small, short-lived tunnel channels (*cf.*, Chapter Three). Because of the trough provided by the preglacial

topography, significant amounts of water were funnelled toward the KGC. Initially this sheetflow overtopped all of the study area, but when it started to channelize, the north-south oriented trough acted like a megachannel (Brennand and Shaw 1994). The subsequent erosion of glaciogenic sediments in this trough is indicated by the paucity of till in the southward continuation of the trough from the KGC to the Sedgewick district. Partly channelized flow was also routed around the higher ground of the Viking upland and swept through the Sedgewick district. As channelization continued, this flow interacted with that water flowing through the north-south oriented trough, deflecting the now active small tunnel channels to the southeast. These channels partly incised through topographic highs with thicker glaciogenic sediments, forming the continuous morphology from scarp to aligned hummock forms (*cf.*, Chapter Three). These small tunnel channels were initially forced over the high ground to the southeast, but then deflected northward into the Irma district and then southward, developing the large glaciofluvial mantle south of Irma (Figure 4.2b, note the linear ridge).

In the KGC the initial stages of this flood event were primarily erosional. This erosion removed almost all the subglacial lacustrine and till sediment and formed the hummocky terrain both adjacent to and, in restricted locations, within the KGC. At this time the meltwater was being conveyed southward from the KGC. As the channelization progressed and the southeast-oriented tunnel channels were being utilized, the flow within the KGC began to be deflected toward the southeast. As the discharge of the flood waned, significant amounts of glaciofluvial sediment began to be deposited. At first the northern inlets deposited most of the sediment at the northern end, forming the arcuate dune forms such as at Site #8. Eventually, the southward connection closed and flows were rerouted by the large ridges in the centre of the KGC. Along the southern part of the KGC, flow through Hattie Lake depression was deflected east-southeast, depositing glaciofluvial sediments in previously eroded channels. The interaction of currents directed from the north and the rerouted currents from the west caused the paleocurrents at Site #11 to be directed east, toward the outlet (Vernon Lake). The combination of dropping discharge and flow rerouting caused the final subglacial deposition to occur in the relatively small channels which had been eroded west-east, across the deposits.

North of the KGC the tunnel channels also underwent a period of erosion and then rapid abandonment. At the last stages of meltwater flow, the main inlet was the only channel delivering sediment to the KGC. It was at this stage in the formation of the KGC that the channel forms were initiated in the KGC. The mantling of hummocky terrain by the glaciofluvial sediments at Sites #1, 2, and 3 occurred at the latest stage of meltwater through this trough.

Late Subglacial

After discharge through these areas ceased, the ice sheet settled back down onto the landscape, only slightly modifying the sediments. Because of the removal of debris from the base of the ice, the basal ice at this time was relatively clean so that deposition of sediments only occurred in a few isolated locations. Also, as the connections between subglacial cavities were cut off, minor depressions collected water and were responsible for the laminated sediments that mantle some hummocky terrain (*cf.*, Chapter Five). Stagnation of the ice lead to the formation of eskers that superimpose hummocky terrain, and hummocky glaciofluvial deposits.. The fact that many of these eskers are oriented obliquely to the channel forms indicates that the piezometric surface had been reoriented by the passage of the main meltwater event. Also, because some of the eskers have undulatory crestlines they must have been formed subglacially.

Postglacial

After retreat of the Laurentide ice sheet, there was a period of relatively cool conditions that account for the formation of the periglacial features present at Site #3. It is also likely that some proglacial meltwater modified the lowest portions of the glaciofluvial sediments that were initially deposited subglacially. It is highly improbable that the sediment and meltwater necessary for formation of the KGC could have originated from the minor lake located at Lac Loranger. There could not have been enough sediment present locally to explain this impressive suite of glaciofluvial sediments and landforms.

Conclusions

Sediments and landforms associated with the KGC are the products of differential erosion and deposition by, first, glacial and subsequently glaciofluvial processes. The majority of the topography visible today is erosional: preglacial and subsequently subglacial. The glacial sediments are mere mantles on top of the bedrock-controlled high known as the Viking upland. The glaciofluvial sediments in the KGC overlie a erosional unconformity that is part of a series of continental-scale unconformities associated with glaciofluvial erosion (Shaw et al. 1998). Because of the rapid deposition, the surface topography of the expansion bar-like deposit is dominated by transverse bedforms that are characterized by unidirectional flow in some locations and flow interference in others.

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CHAPTER FIVE: FORMATION OF HUMMOCKY TERRAIN IN EAST-CENTRAL ALBERTA: IMPLICATIONS FOR ICE SHEET DYNAMICS AND HYDROLOGY.

Introduction

Hummocky terrain (HT) is one of the most common landform types in glaciated regions. The presence of a hummocky landscape is often presumed to represent deposition during the last stages of ice stagnation, although several different hypotheses exist (Table 5.1). Although the presence of hummocky landforms does not necessitate formation by stagnant ice, HT has been used to reconstruct former ice margins and thus has been implicated as an important paleoclimatic indicator (e.g., Dyke and Prest 1987; Klassen 1989). Using HT to infer former ice margins has recently been called into question, suggesting that HT may have been formed subglacially, far from the ice margin (Rains et al. 1993; Shaw et al. 1996; Munro and Shaw 1997; Beaney 1998). On the basis of these recent findings, and a lack of consensus on the genesis of hummocky landforms, the descriptive term HT will be used in this paper, although the more commonly used morpho-genetic term, hummocky moraine, is still endorsed by many scientists (e.g., Eyles et al. 1999).

HT is composed of tracts of hillocks and depressions arranged in chaotic to aligned patterns. The presence of aligned tracts of hummocks has often been used to suggest that glaciotectonic structures in the ice "controlled" the pattern of deposition of the hummocky terrain (e.g., Rains and Shaw 1981; Krüger 1996). The sizes and shapes of individual hummocks within a hummock tract are often highly variable. The tops of individual hummocks may be flat, convex-up, or contain central depressions with raised margins. The flat-topped hummocks are often larger than other forms and have been referred to as moraine plateaux (Hoppe 1952; Stalker 1960) or ice-walled-lake plains (Ham and Attig 1996). Hummocks with a central depression have been referred to as prairie mounds, rim ridges, or ring ridges (Stalker 1960; Parizek 1969; Aartolahti 1974). The variation of hummock shape within and between different hummock tracts indicates that the formation of HT is complicated and likely a composite of several different, but related processes.

Problem Statement

In Chapters Two and Three attention was drawn to the widespread erosion/removal of glaciogenic material in large portions of east-central Alberta. Removal of large amounts of glaciogenic sediments in the Torlea Flats (Chapter Two) was nearly complete, with only residual islands of diamicton (till) left perched on bedrock-cored linear landforms or in preglacial valleys.

Table 5.1: Pertinent theories of hummocky terrain (moraine) formation.

Hypothesis	Selected Authors	Evidence
Supraglacial reworking	Gravenor and Kupsch 1959; Rains and Shaw 1981; Benn 1992; Andersson 1998	• stacked units of flow diamictons • weak clast fabrics
Subglacial pressing	Hoppe 1952; Stalker 1960; Shaw and Ashley 1988; Eyles et al. 1999	• subglacial sediment • strong clast fabrics toward the centre of the landform • theoretical modelling
Moulding of subglacial till	Aario 1977	• association with drumlins and flutings
Discontinuous deposition of lodgement till	Menzies 1982	• theoretical modelling and possible linkage to drumlin formation
Subglacial groundwater intrusion into permafrost	Boulton and Caban 1995	• theoretical modelling of groundwater flow and ice-marginal permafrost
Stacked layers of debris-rich ice	Möller 1987	• presence of subglacial meltout till over lodgement and lee-side tills
Ice marginal stacking	Krüger 1996; Sharp 1985	• investigations of contemporary processes
Subglacial fluvial erosion	Rains et al. 1993; Shaw et al. 1996; Munro and Shaw 1997; Beaney 1998	• various types of sediment within the hummocks that did not coincide with the forms • truncation of bedding within the landforms
Subglacial fluvial deposition	Holden 1993	• plane and cross-bedded fluvial sediments that were consistent with the hummock form • stoss and lee gradations in the sediment

As discussed in Chapter Two, this removal is best explained by subglacial fluvial processes. In Chapter Three various erosional channelized landforms in the study area were put into context with this regional scale erosion. It was hypothesized that the interaction between the preglacial topography, preglacial drainage systems, and subglacial dynamics/hydrology were responsible for the existing landform assemblages. The erosional channels described in Chapter Three are often directly associated with HT which is found within the channels, on interfluves, and in large tracts in the study area. The geomorphology of the area indicates that a classic ice-stagnation origin for the HT inadequately explains the formation of the observed landforms. Several hummocks are composed of bedrock and in some locations HT is overlain by subglacial eskers. In addition, erosional channels often truncate HT and many channels contain glaciofluvial sediments, HT, and eskers. These observations indicate that HT must have formed subglacially.

Although the landform associations in the northern Viking Moraine demonstrate that HT was formed subglacially, there are several processes that may have been responsible for their evolution (Table 5.1). Three major questions must be answered to elucidate the formative processes. First, what was the genesis of the sediments in the hummocks? Second, what processes were responsible for *emplacing* the sediment contained in the hummocks and were these the same as those which *formed* the sediment? Third, were these processes responsible for the hummock shapes? To answer these questions the sediment type and architecture must be investigated in context of the topography and associated landforms.

Study Area

The study area is located near the northern limits of the Viking Moraine (Warren 1937; Bretz 1943) in the vicinity of the hamlet of Kinsella (Figure 5.1a). This area is dominated by HT with a local relief of 5-20 m (Shetsen 1990), although glaciofluvial channels partly dissect the western and southern part of the area. This extensive tract of HT is situated on a broad rise referred to as the Viking upland (Chapter Two) that represents the preglacial and postglacial drainage divide (Figure 5.1b). The Viking upland is gently undulatory with several elevated zones that contain the best-developed HT. These undulations are bedrock controlled and reflect the preglacial topography. The lower zones within the Viking upland are often occupied by glaciofluvial landforms in the west and glaciolacustrine basins in the east. These glaciolacustrine and glaciofluvial sediments onlap the hummocks, muting their topographic expression. The eastern margin of the Viking upland is defined

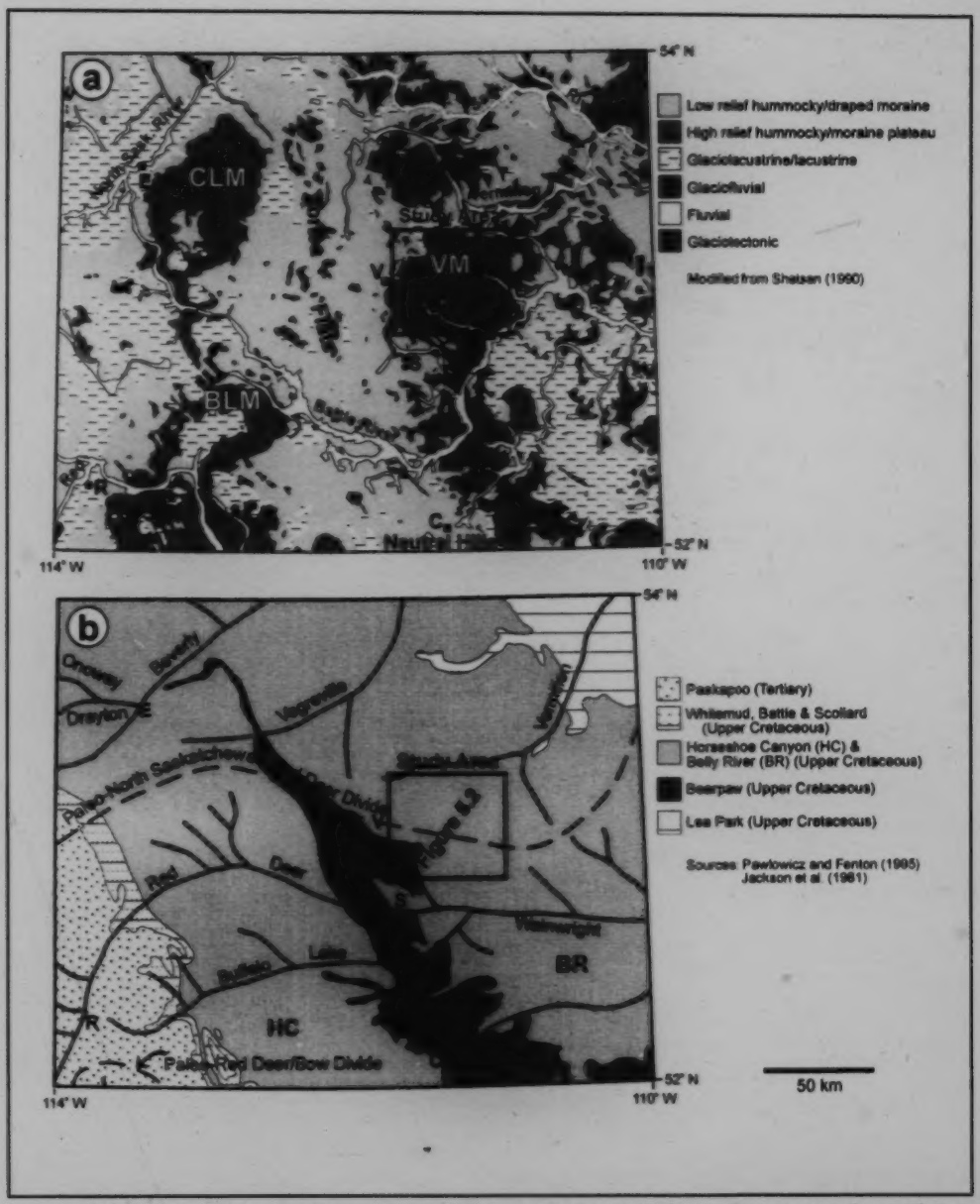

Figure 5.1: Setting of the study area in east-central Alberta. (a) The study area was located on a large, bulbous portion of the Viking Moraine (VM), near the present drainage divide between the Vermilion and Battle Rivers. This elevated area is referred to as the Viking upland. (b) Generalized bedrock formations and the location of preglacial valleys and drainage divides. The study area was located on the preglacial divide between the ancestral Vermilion and Wainwright valleys. C-Coronation, E-Edmonton, K-Kinsella, R-Red Deer, S-Sedgewick, V-Viking, CLM-Cooking Lake Moraine, BLM-Buffalo Lake Moraine.

by Buffalo Creek. On the western margin of the upland, the Torlea Flats separate the HT from the Buffalo Lake Moraine located ~ 100 km to the west.

Geomorphology

HT in this part of the Viking Moraine shows a variety of shapes, spatial arrangements, and sizes. Hummocks seldom occur in isolation but, rather, are arranged in linear to non-directional clusters. Clusters of hummocks may consist of unidimensional elements or larger forms surrounded by smaller, satellite elements. Individual hummocks may be flat-topped, low-centred, or high-centred. In addition, they may be circular, hexagonal, elliptical, or linear in plan view. The variation of shape and pattern, often over small distances, indicates that variations in hummock morphology occurs along a continuum rather than in discrete changes between genetic types. Thus, any morphologic classification will likely not be very useful for genetic interpretations but, rather, identification of the setting of these shapes will be more informative. Although a strict classification is not attempted, a review of common hummock shapes and patterns, present in the study area, will be undertaken.

Shape of Individual Elements

The largest elements found in HT are the moraine plateaux (Stalker 1960). These features are not common in the present study area but are very prominent because of their immense size. Moraine plateaux range from 500 to 1800 m in diameter and are always the highest features in the area, reaching 25-30 m above the surrounding terrain (Figure 5.2). Crests of adjacent hummocks are seldom as high as the moraine plateaux and usually 10-15 m lower. The moraine plateaux seldom have raised marginal rims as previously reported from elsewhere (Hoppe 1952; Stalker 1960; Parizek 1969; Aartolahti 1974; Ham and Attig 1996) but, rather, their margins are abrupt. These features often have a hexagonal shape with indented margins defined by the flanking depressions.

Circular, high-centred hummocks are present in the area but are not as prevalent as some of the features described later. They are significantly smaller than the moraine plateaux, seldom exceeding 300 m in diameter and 25 m in height. Usually they are 100-200 m in diameter and 5-15 m in height. Although circular elements are present, elliptical to highly elongate elements are more common (Figure 5.3). Interspersed with high-centred hummocks are those with central depressions. In this portion of the Viking Moraine low-centred hummocks are more common than high-centred

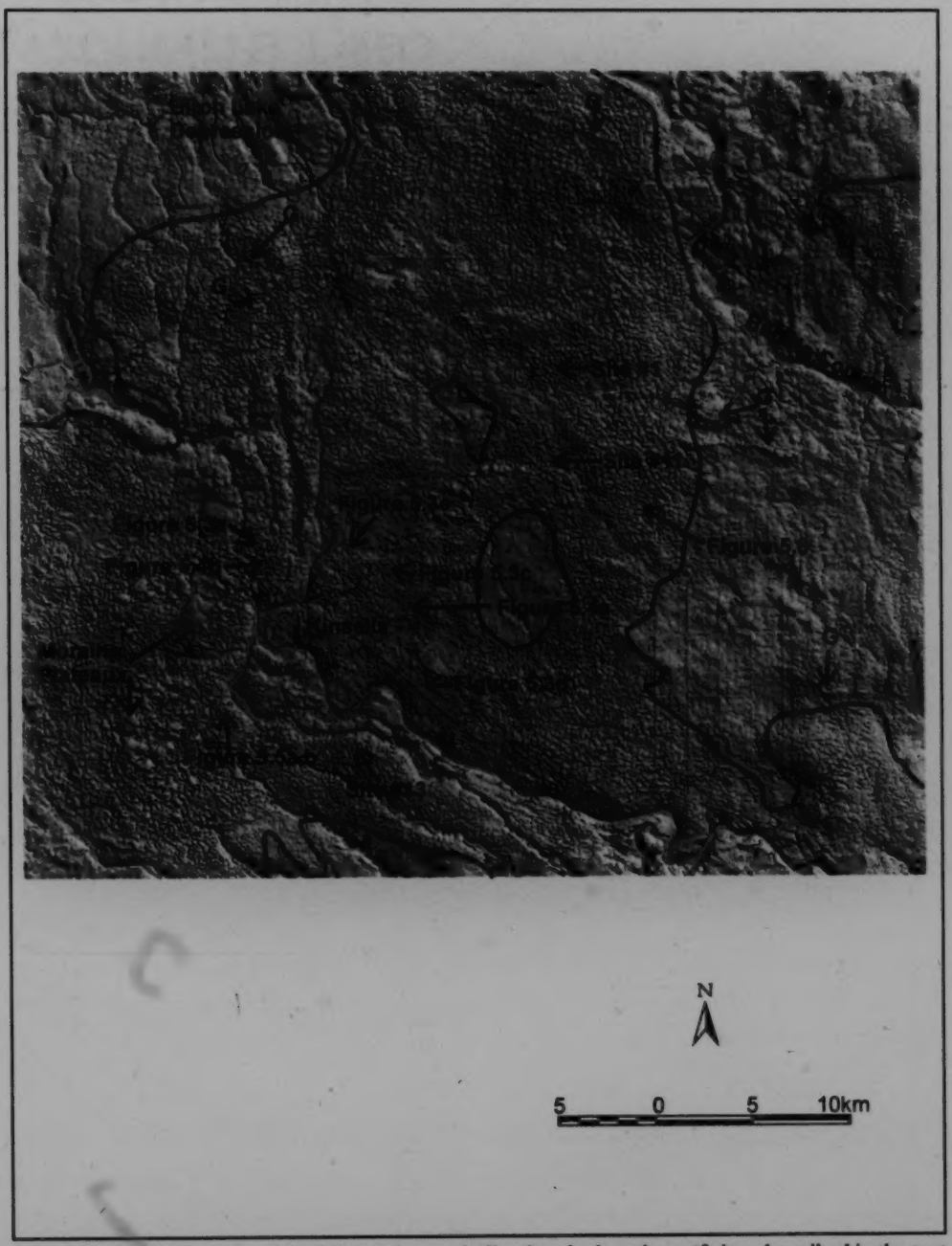

Figure 5.2a: Hillshade model of the study area indicating the locations of sites described in the text and the general outlines of main hummocky terrain areas (HT). Solar azimuth/angle=45/40. Compare the distribution of the rugged HT and the elevation map in Figure 5.2b. Note the location and topographic expression of the moraine plateaux and the glaciotectonic terrain (G).

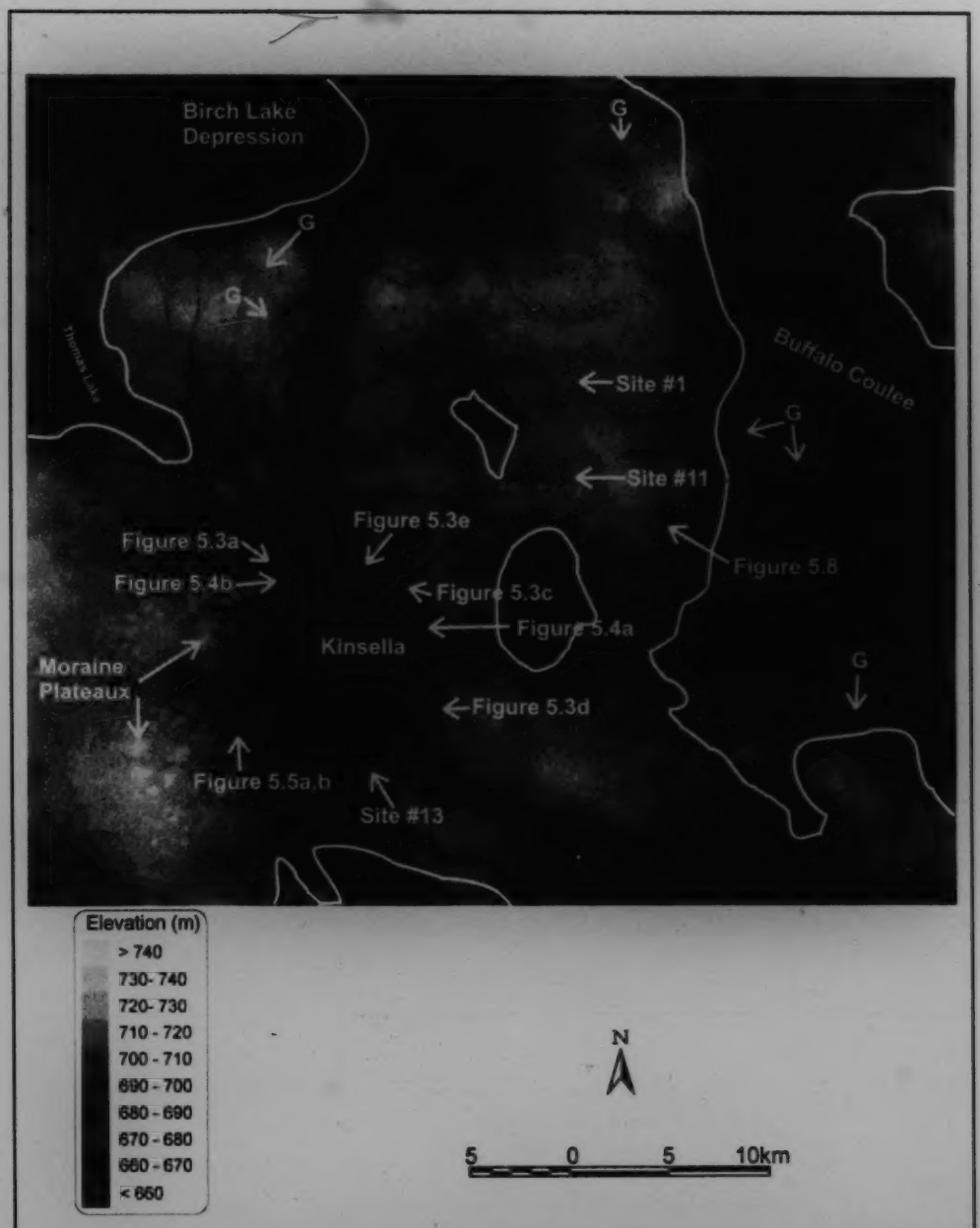

Figure 5.2b: Classed elevation map of the study area. The higher relief hummocky zones of the Viking upland are situated on the higher elevated zones, whereas the lower relief HT is in the shallow depressions. This topographic control does not affect the distribution of low-centred versus high-centred hummocks, only the relative height. Note the topographic setting of the glaciotectonic terrain (G) and moraine plateaux.

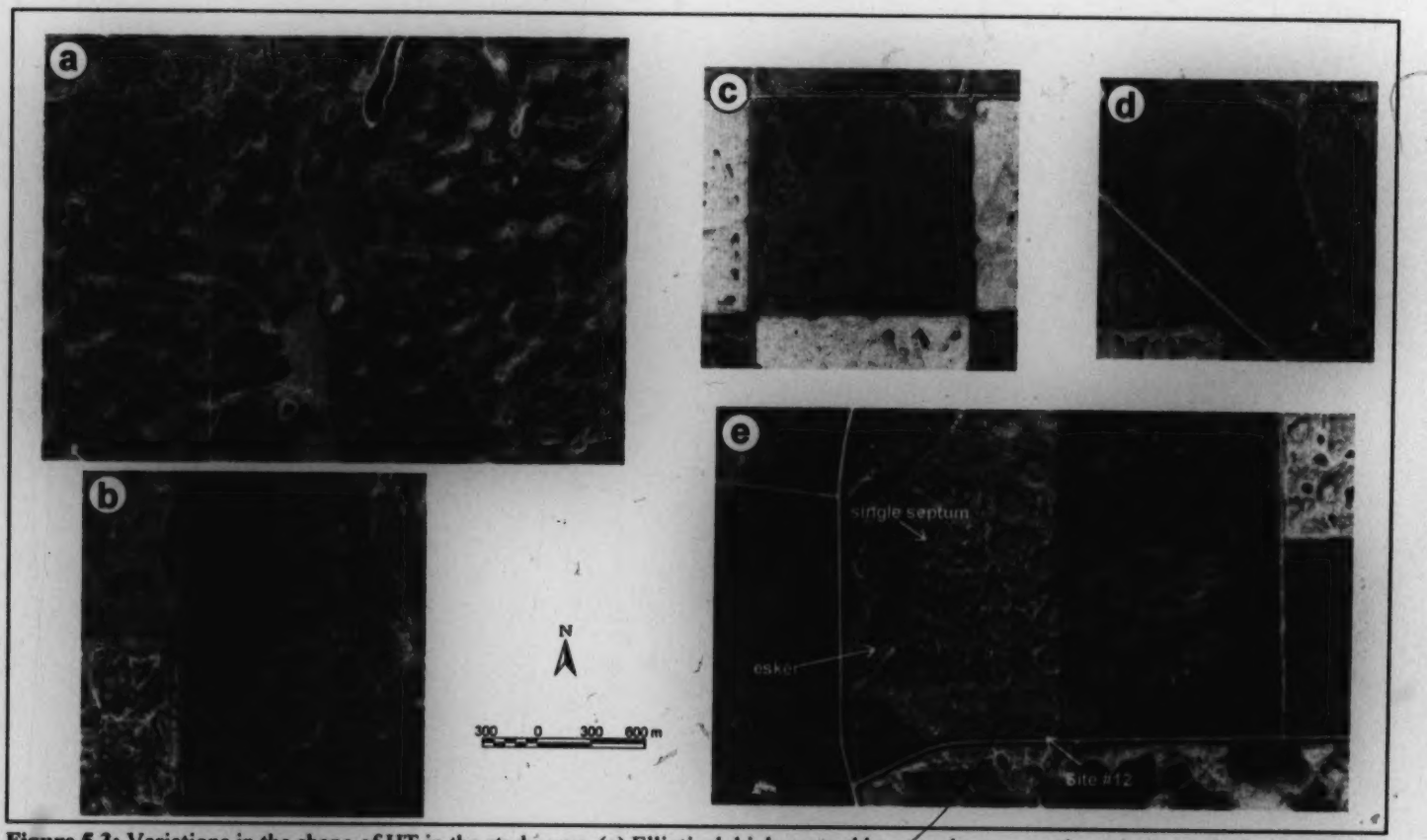

Figure 5.3: Variations in the shape of HT in the study area. (a) Elliptical, high-centred hummocks on a northward-sloping bedrock upland. Note that in many places the elliptical forms merge to form bulbous ridges that trend E-W. (b) Non-directional clusters of low-centred hummocks and poorly developed hummock chains. Note that many have double septa separating individual elements. (c) Isolated, low-relief elements, some of which have incomplete rims. (d) Low-relief, flat-topped hummocks with smaller satellite elements. (e) Low-centred hummocks with single and double septa. Note the esker.

ones. The variety of intermediate shapes indicates a shape continuum between these two types. The central depressions are usually elevated above the ground surrounding the hummock, but there are some features where the depressions extend below the surrounding ground surfaces. Low-centred hummocks defined by continuous raised-margins have been referred to as prairie donuts (Stalker 1960), ring ridges (Aartolahti 1974), and rim ridges (Parizek 1969).

Variants of prairie donuts are present throughout the study area and are by far the most distinctive landforms. One type of variant looks like coffee beans with a linear depression bisecting an otherwise elliptical hummock. These coffee bean-like shapes may constitute well-defined hummocks but it is equally common for hummocks to have one end open, producing a horseshoe shape. Horseshoe-shaped hummocks often open downslope, though there are many examples of two adjacent elements opening in opposite directions. Other variants of hummock forms are straight to sinuous ridges, also composed of diamicton. These ridges may be a lengthened arm of a horseshoe-shaped hummock, isolated features, or connected to clusters of other HT elements. All the features mentioned above are identifiable members of a continuum as it is easy to find intermediate forms. Because of this morphologic continuum, and the fact that they are found immediately adjacent to each other, it is problematic to invoke differential genesis.

Topography/Landform/Pattern Relationships in Hummocky Terrain

Circular, high-centred hummocks are found as part of chaotic HT and in the areas between moraine plateaux. Sometimes circular hummocks are found in clusters, either with equidimensional elements or one large hummock surrounded by smaller, satellite elements. Elliptical elements are often arranged in patterns where the long axes are roughly parallel. In some locations the alignment of elliptical elements is so well developed that the HT could be referred to as "controlled" (Rains and Shaw 1981). These elongate elements may merge together to form undulatory ridges with superimposed hummocks. These ridges are most common on the northward-dipping slopes where they are associated with glaciotectonically disturbed bedrock (Figure 5.2). In some locations, elliptical and circular high-centred hummocks are found in linear groupings. In these cases they are invariably associated with low-centred elements.

Low-centred hummocks are arranged individually, in tight clusters, and in linear chains. It is common to find one large hummock forming the centre of a cluster, surrounded by smaller satellite elements. Clusters with roughly equidimensional elements are more common. Coffee bean

elements are found in tracts where the alignment of the central depressions may or may not be coincident. In some locations there is a vague rectangular pattern where adjacent coffee bean-like hummocks have perpendicular orientations. Straight or sinuous chains of low-centred hummocks are very common in the study area. These chains can be composed of nearly circular or rectangular elements separated by single- or double-crested septa. It is common for chains in a restricted area to be roughly parallel but perpendicularly oriented chains are also present. Septa between "links" in the hummock chains can have a similar elevation to the lateral margins but may also be depressed or absent. When septa are absent, the chains are more aptly described as sinuous, sub-parallel ridges. The sinuosity is often scaled to the adjacent hummocks, again suggesting a continuum of forms. Although these ridges are nearly always sub-parallel there are documented cases of similar ridges being divergent or convergent (Aartolahti 1974, his Fig. 5). Where the ridges are not paired they are difficult to distinguish from eskers. Stalker (1960) interpreted such single ridges as 'till-filled eskers' formed as glaciogenic material was squeezed up into an empty conduit. Diamictons have been documented in esker cores, surrounded by glaciofluvial gravel (Brennand 1993). In these cases, the diamicton cores are inferred to be diapirs of deformable sediments that were forced into a low-pressure conduit.

Hummock morphology is only partly affected by the topographic setting because both high- and low-centred hummocks occur in all settings. However, the height of individual elements is greater on the elevated portions of the Viking upland (Figure 5.2). In addition, these elevated areas generally have thicker stacks of glaciogenic sediments, so there is a direct linkage between regional scale bedrock topography, glaciogenic sediment thickness, and landform scale. Where the vertical scale of hummocks is closely linked with the topography, the plan shape of individual elements is not so obvious. Although high- and low-centred hummocks do not have a preferred topographic setting, the size of the central depression is relatively large for those elements located in areas of shallow glaciogenic sediments. It is not uncommon to find low-centred hummocks in areas with thick glaciogenic sediments or areas with bedrock exposed between the hummocks.

The patterns in the HT do not have any obvious topographic control. Hummock chains and clusters occur in both relatively low and elevated portions of the Viking upland. Sinuous and rectangular patterns in hummock chains occur in flat and slightly sloping areas. In Figure 5.4, the parallel chains of hummocks are situated on a gentle slope that dips toward the northeast and Hattie Lake. Rectangular patterns are present on the northeast slope of an elevated area (Figure 5.5). In

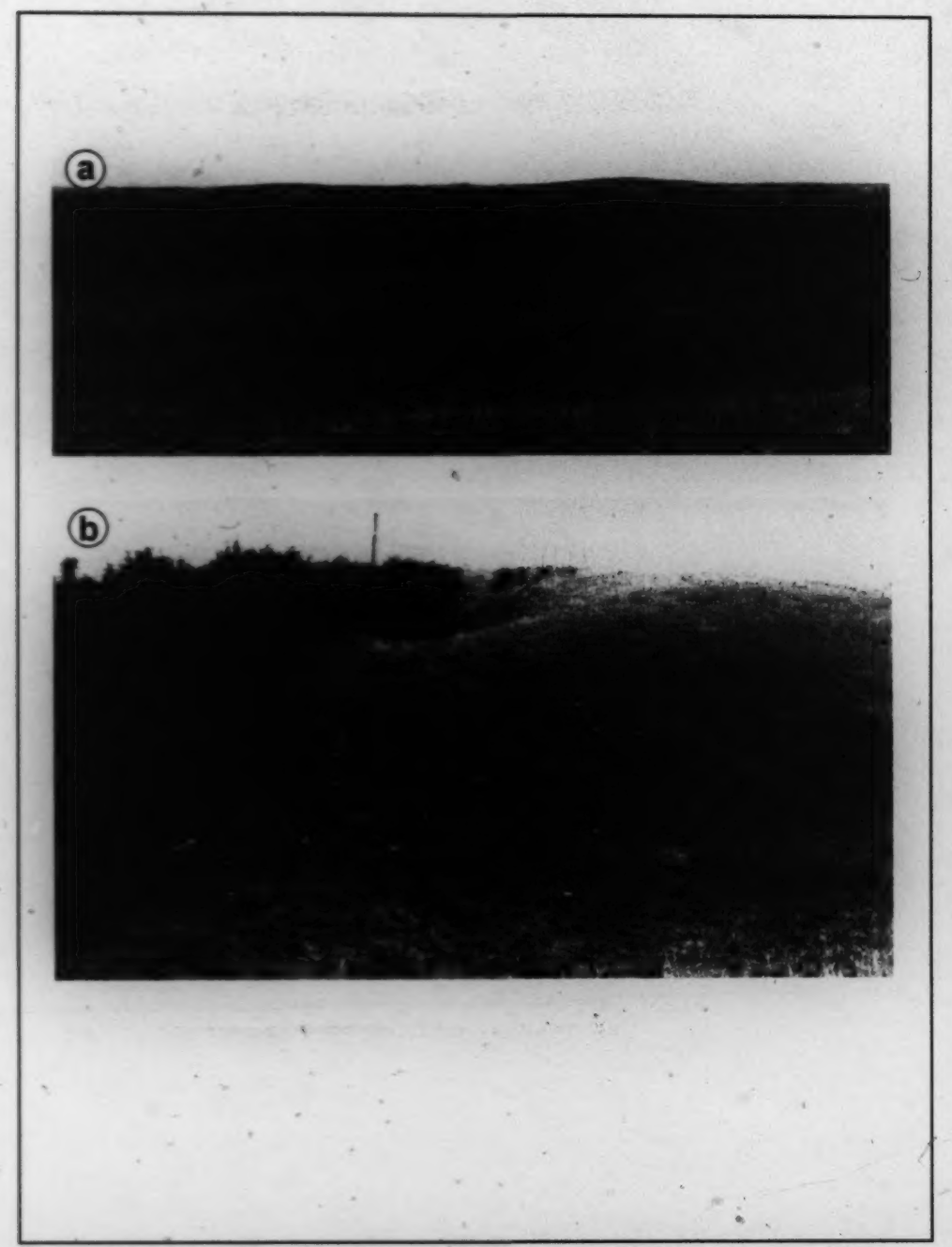

Figure 5.4: Examples of low-centred hummocks. (a) Low-relief, low-centred hummock in an area of thin surficial sediments. Note the consistent elevation of the ridge. (b) Low-centred hummock in areas of thick surficial sediments. Note the relative size of the depression compared to (a).

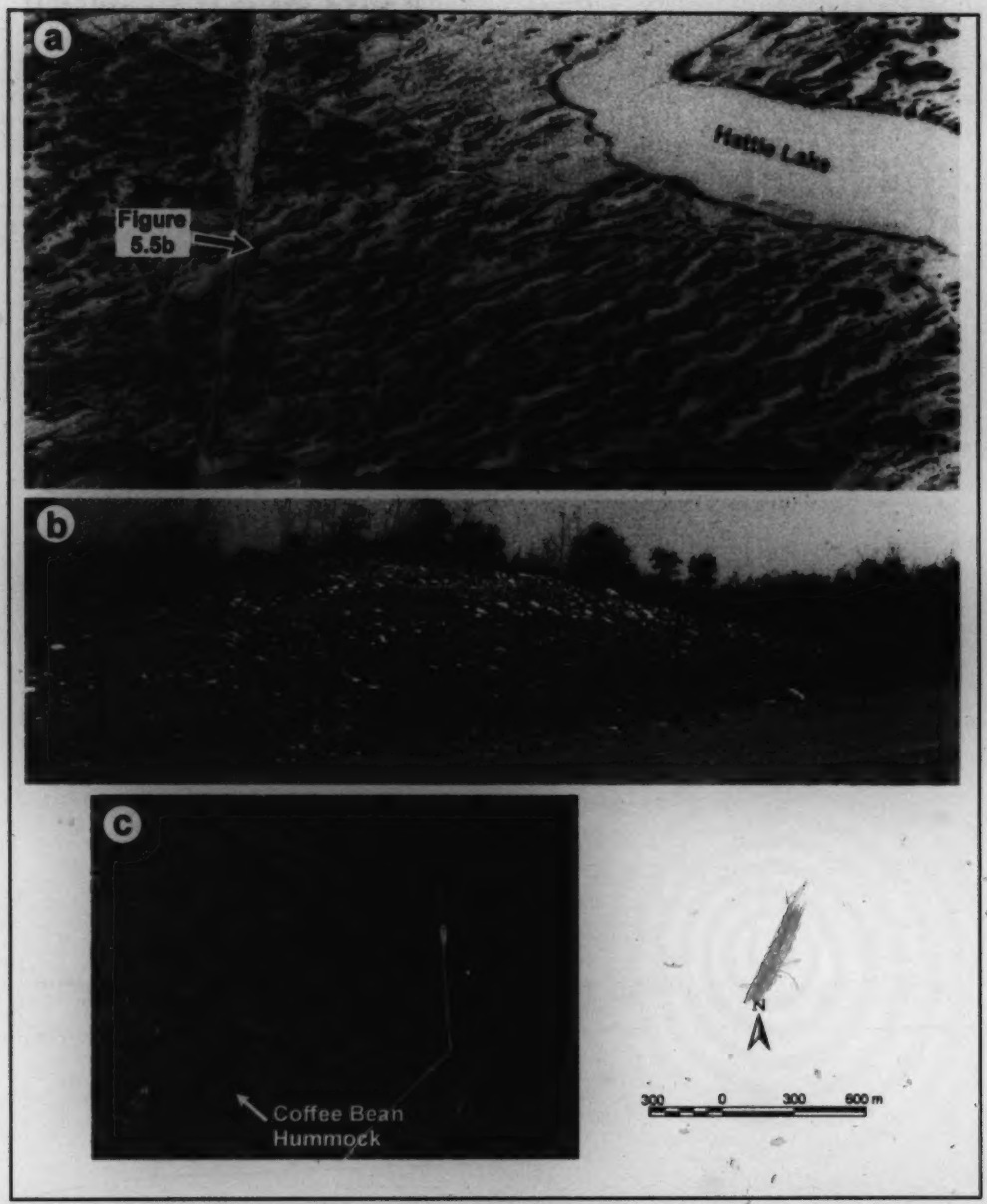

Figure 5.5: Linked chains of hummocks. (a) Roughly equidimensional low-centred hummocks linked in linear chains. There is a close association of paired sinuous ridges and the chains of hummocks. Note that the sinuosity of the ridges is similar in scale to the size of the hummocks. Photo courtesy of J. Shaw. (b) Exposure transverse to one of the ridges in (a). The sediment in the ridges and chains of hummocks is dominated by stony diamict and often is capped with glaciofluvial sediments. (c) Vague rectangular pattern to chains of hummocks. At this location the low-centred hummocks are more rectangular and are associated with coffee bean-like shapes.

these two cases the chains are either oriented parallel or perpendicularly to the regional slope. Sinuous chains are more common in the flatter, lower areas of the upland and are typically not so long as more linear chains. In nearly all locations where linear chains are present, they are oriented northeast-southwest. This preferred orientation occurs despite different topographic settings throughout the area.

Sedimentology

Sediment Types

HT in this area is composed of different combinations of four sediment/rock types: lacustrine, bedrock, glaciofluvial, and diamicton (till). Lacustrine sediment is found at several locations and often contains several species of gastropods. Contacts with this sediment are always contorted/sheared indicating that the sediment has been displaced. Where bedrock is found in hummocks it is usually undeformed, although minor folding does occur. Glaciofluvial sediment is found enclosed within the hummocks and on top of the hummocks as mantles or lags. In either case the sediment is defined as glaciofluvial on the basis of the presence of Canadian shield clasts. Diamicton (till), contained in HT, is commonly banded with inclusions of grey, silty pods of material. These sediments are massive to laminated and often contain discontinuous silt and sand partings. Diamicton usually comprises most of the volume of individual hummocks but is often arranged in complex stacks separated by low-angle shear planes. These diamictons often have intermediate to strong clast fabric orientations, indicating a subglacial origin.

The four sediment/rock types are seldom found in the same hummock. Rather, the composition is spatially variable and loosely linked to the topography and associated landforms. The arrangement of sediment within the HT is highly variable, often indicating glaciotectonic processes were important in their emplacement. At other locations the sedimentary architecture does not indicate that these processes were important. Thus, a simple model of glaciotectonic stacking of materials to form the HT is insufficient. To address the variability of sedimentary characteristics, several sites will be discussed and placed into a generalized conceptual model of hummock formation.

Site #1 (UTM: 12U 477000E, 5884500N)

The exposure at Site #1 is a north-south oriented roadcut that crosses the middle of the

hummock, creating a section with western exposure (Figure 5.2). This hummock is one of the highest in the immediate vicinity, although there is a higher zone of HT to the north. It is high-centred and approximately10 m in height. It is elliptical in plan with the long axis trending north-northwest to south-southeast. The upper 3-4 metres of the hummock is exposed and contains predominantly dense, matrix-supported diamicton with a secondary component of laminated sediments.

Sediments in the hummock are arranged so that the south and southwestern sides of the feature are dominated by compact, vaguely banded diamicton (Unit 1 in Figure 5.6) containing sorted stringers of sand and granules. These stringers are parallel to the banded structure of the diamicton and a few are folded. In addition to the thin stringers of sorted sediment there are also several angular blocks of sand. The bedding in these intraclasts is, for the most part, undeformed. The banded structure in this unit is horizontal in the centre of the hummock, gently dipping to the southwest in the southern portion of the feature. Three clast fabrics taken from this unit indicate a very strong orientation that ranges from the SW to the WNW (Figure 5.6). These fabrics have S_1 values greater than 0.700 which are indicative of deposition by meltout or lodgement processes (Dowdswell and Sharp 1986; Hicock et al. 1996). Because of the presence of sorted material in the unit, emplacement by meltout processes is the preferred interpretation. Normal faults are absent and the banding appears to be primary. No extensive units of sorted sediments were found within this unit.

The contact between Units 1 and 2 is characterized by a combination of gradational and abrupt, erosional contacts. Along the upper part of Unit 2, the contact with Unit 1 is a shear plane, whereas the lower, southern contacts are gradational between a very dense, dark diamicton and the Unit 1. Near the contact between these two units there are faint bands of crushed shells that presumably originated in Unit 3. This lowest unit is interfingered with Unit 3 along its northern margin (Figure 5.7a). At this location it is separated from Unit 3 by planar, subhorizontal shear planes (Figure 5.7b).

Unit 3 is composed of laminated sediments that in places are highly contorted and in others relatively undisturbed (Figure 5.7). These laminated sediments invariably contain crushed shell fragments which delineate individual beds. The bedding is often folded and where these folds are near a contact they are truncated by a subhorizontal shear plane. In many locations these subhorizontal shear planes separate components of this unit and comprise the unconformities

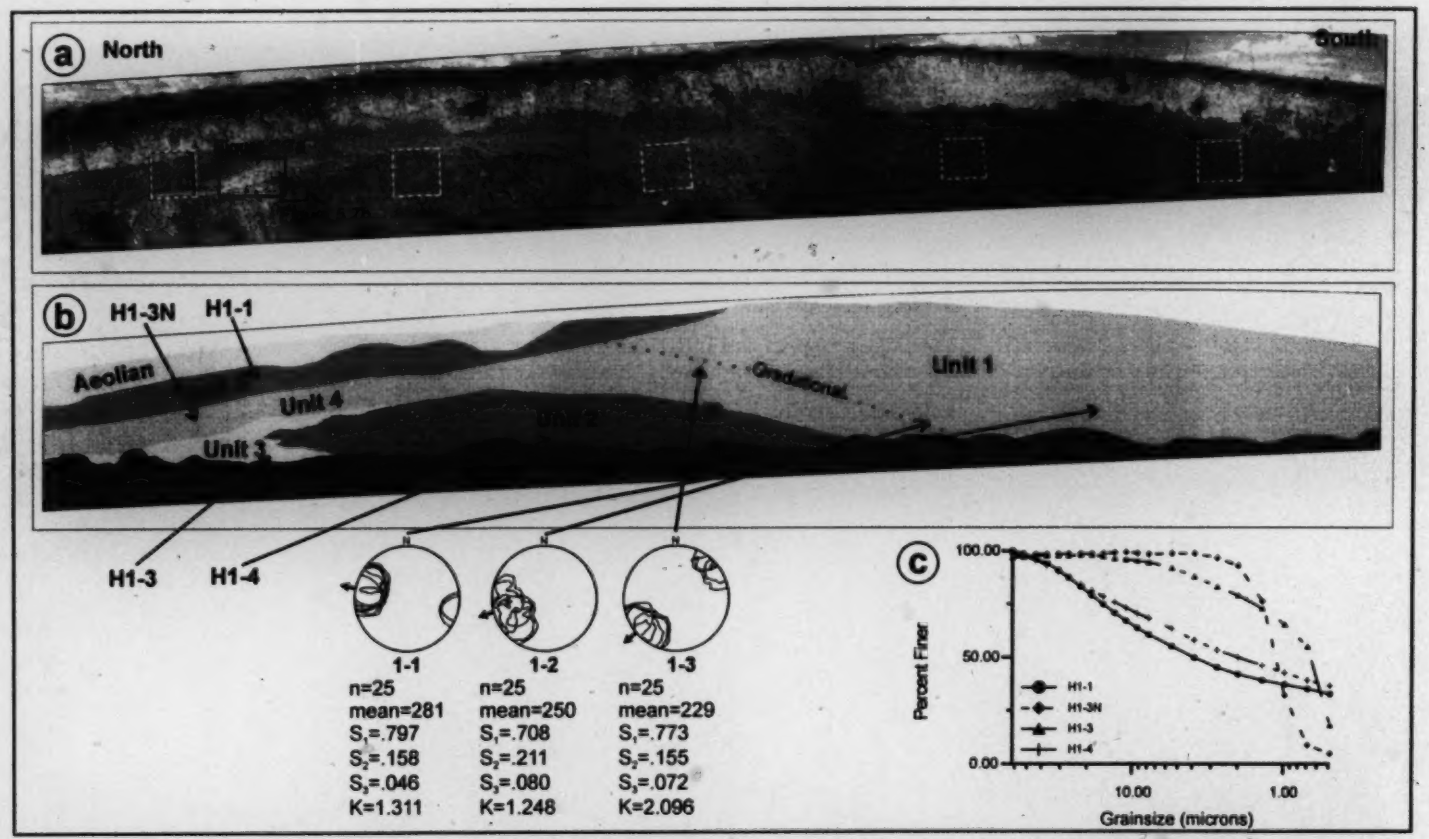

Figure 5.6: Sediments exposed at Site #1. (a) Attitude of the exposure. Note the whitish unit on the left side of the section which contains the crushed gastropod shells. Quadrats are 1 m^2. (b) Interpretation of the sediments in (a). Unit 1 is a vaguely banded diamicton containing sand stringers that dip toward the southwest. Units 1 and 2 are separated by shear planes. Unit 1 is gradational with unit 4 which overlies unit 3, containing the crushed shells. The locations of clast fabrics taken at this site are indicated, as are the textural analyses of the matrix of the diamicton.

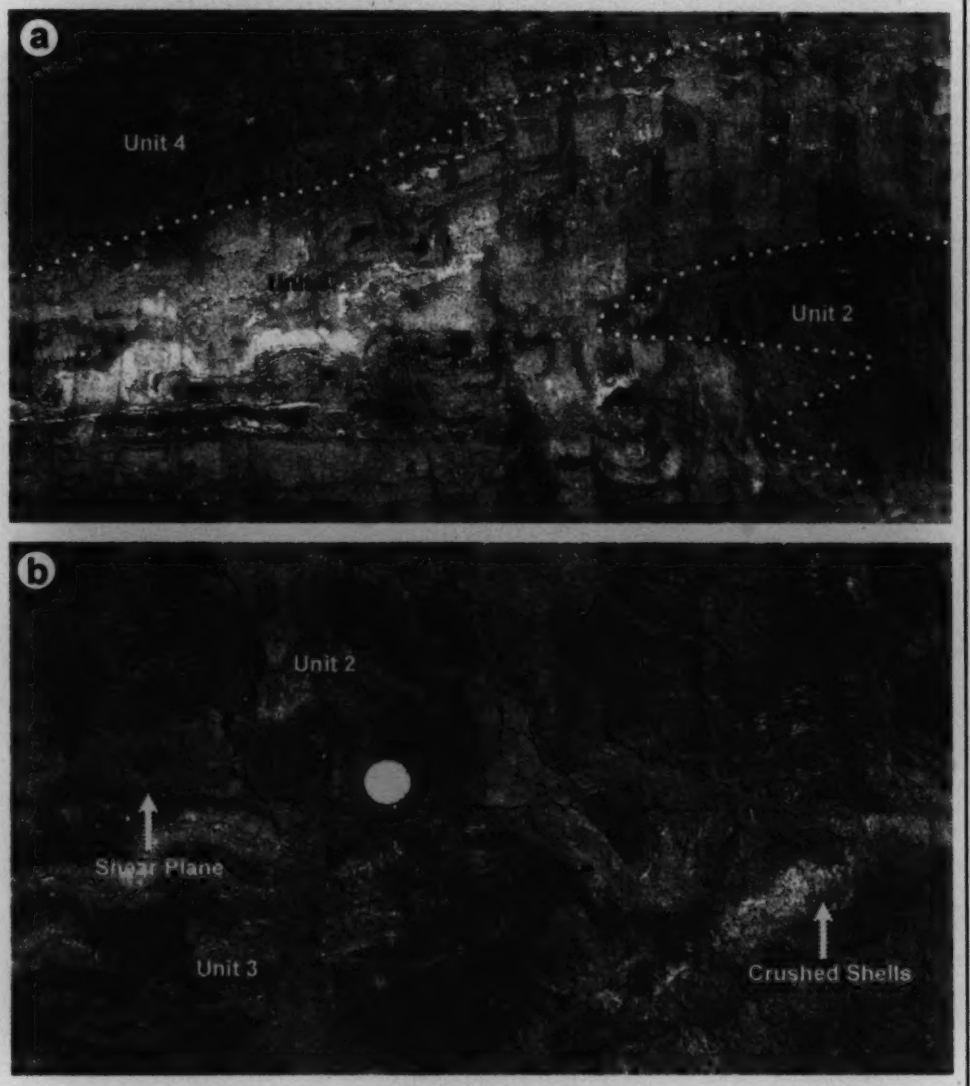

Figure 5.7: Close-up of the contacts between Unit 3 and enclosing sediments. (a) Interfingering of Unit 2 with 3 is apparent by the multiple shear planes. The contact with the laminated Unit 4 is abrupt and unconformable. (b) close-up of one of the shear planes separating Units 2 and 3. Note the lack of mixing and the planar contact. This shear plane dips gently toward 70°.

between adjacent units. In most cases the shells that are contained in this unit are crushed into tiny fragments. However, there are some locations where the shells are intact. The crushed shells are predominantly found in this unit but are also found incorporated into Unit 1. The assemblage of gastropods found within this unit will be addressed in a later section.

Unit 4 is a laminated sediment with well-defined rhythmites. This unit has a blocky structure and drapes the underlying, sheared Unit 3 (Figure 5.7a) in the northern part of the section. The laminations are oriented parallel to the contact with Unit 3 and exhibit no post-depositional reworking. The upper contact of this unit is gradational with Unit 5 which is characterized by a diamicton with a sandy matrix and few large clasts. This upper unit is not consolidated like the lower diamictons but does contain faint banding that, like Unit 4, parallels the surface of the landform. This unconsolidated diamicton is overlain by aeolian sediment.

Site #8 (UTM: 12U 481750E, 5877400N)

The exposure at this site is located in the top of a hummock that is part of a field of low-centred elements, although there are some high-centred elements in the immediate area (Figure 5.8). The hummocks to the east of this site are arranged in chains that have a dominant orientation northeast-southwest, although some elements are perpendicular to this. Several sites in this vicinity will be described (Sites 4, 7, and 2). Site #8 is cut into a coffee bean-shaped hummock on the eastern side of the feature. The upper 4 m of the sediment was exposed, which was approximately 1/3 to 1/2 of the total height of the feature.

Most of the exposure is composed of a dark grey compact diamicton (Unit 1). This diamicton contains a significant component of sand and pebbly-sand beds that dip toward the northeast. These intrabeds dip toward the flanks of the hummock at a lower angle than the surface slope. One normal fault interrupts this characteristic and one portion of the diamicton has been rotated (a in Figure 5.9b). The displacement along this fault is about 40 cm. Two clast fabrics taken from this diamicton indicate an intermediate to weak orientation (S_1 values of 0.663 and 0.515). The vector means indicate orientations toward the northeast to east (roughly parallel to the long axis of the elliptical hummock).This unit is overlain by Unit 2 in both the southern and northern parts of the hummock. The contact with Unit 2 is gradational and the texture is virtually identical (samples H8-3 and H8-2-1 in Figure 5.9c). The distinction between these two units is made on the compactness of the diamicton. The identical grainsize distribution and the gradational contact suggest that they

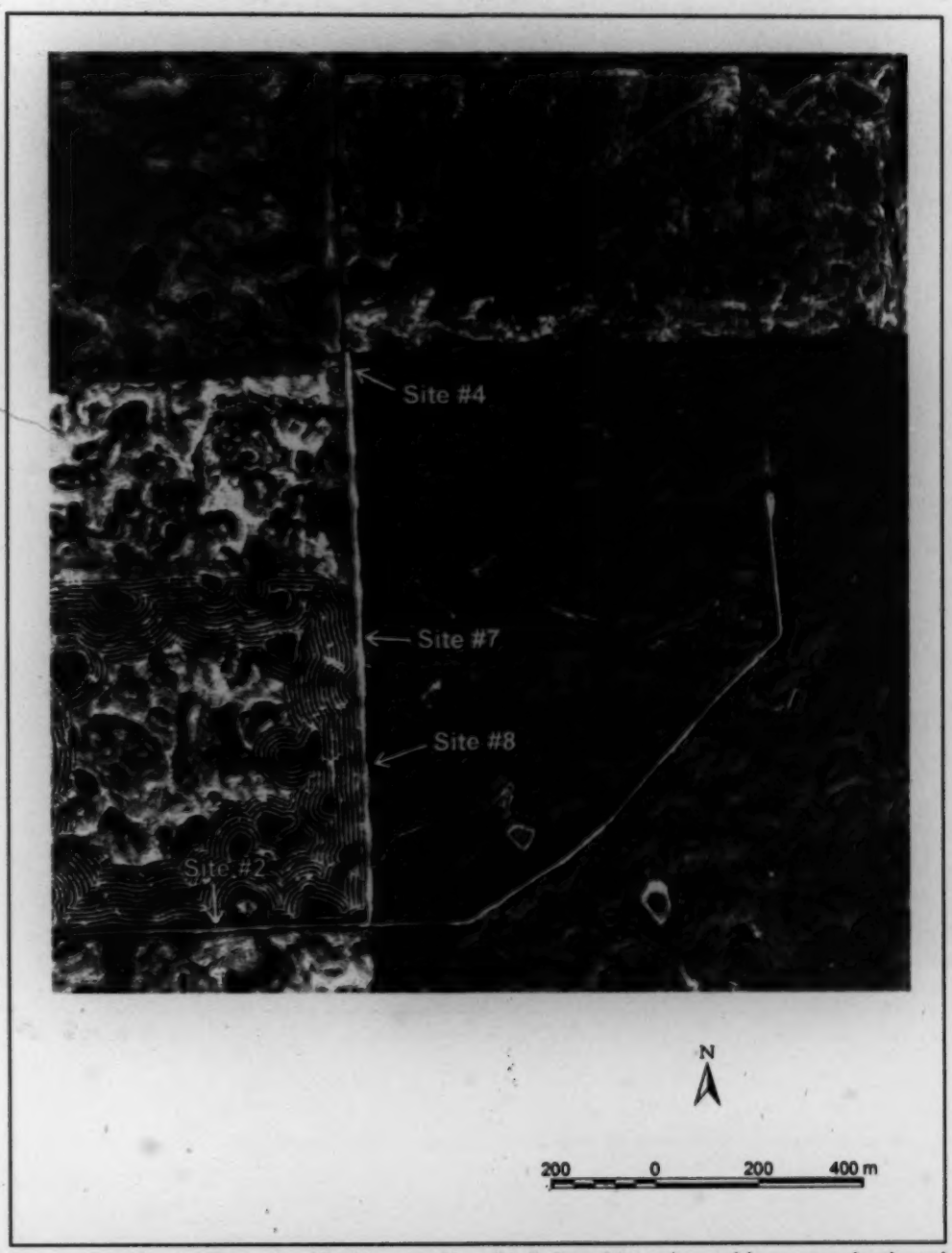

Figure 5.8: Site locations described in text. Sites #4, 7, 8, and 2 are located in an area dominated by low-centred hummocks. Many of the hummocks are coffee bean-shaped whereas others are more rectangular with a pronounced ridge. Note that many of the linked features have broad single-ridged septa.

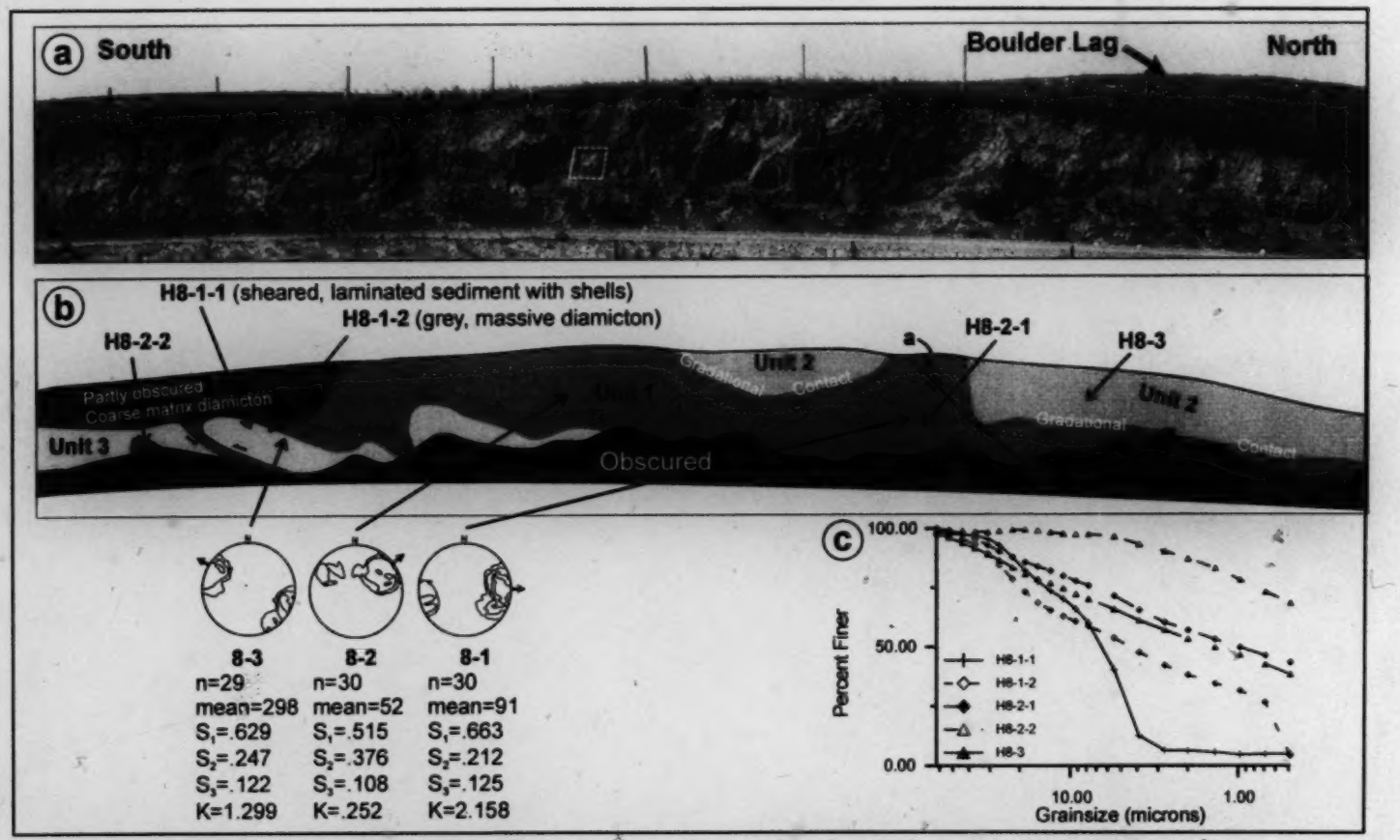

Figure 5.9: Sediments at Site #8. (a) The attitude of the sediments with a prominent boulder lag at the surface. Scale is 1 m^2. (b) Interpretation of the sediments. Unit 1 is a dark grey diamicton with a significant component of sorted sand and pebbly-sand stringers that dip to the northeast. These intrabeds dip at lower angles than the surface slope. Note the normal fault at (a). Clast fabrics are indicated. (c) Textural information on the units.

formed as part of a continuous process.

Unit 3 is below the bulk of Units 1 and 2 and is important for inferring the formation of the hummocky terrain in the area. This unit is composed of a grey, fine-grained material that, as at Site #1, contains significant amounts of crushed and intact shells. There are numerous shear planes within this unit that contain crushed shells. Between the shear planes the laminated sediment may be folded but the laminae and shells are largely intact. The presence of these multiple shear planes indicates that stacking of the sediment occurred and the lack of crushing of the shells between the shear zones indicates that the sediment moved *en masse* rather than as a continuously deforming layer. These shear planes dip toward 70-90° at between 5-15° from horizontal. The facts that this unit is found below the diamicton (Units 1 and 2), and that diamicton is intercalated with the thrust sediment, suggest that the sediments were emplaced at the same time. In addition to this laminated sediment, glaciofluvial gravels are found within the thrust sediment. These gravels are matrix-supported, clasts are well-rounded, and Canadian shield lithologies are present but rare.

Site #4 (UTM: 12U 481750E, 5877800N)

This roadcut is located 400 m directly north of Site #8 and exposes the centre of a low-centred hummock. The eastern rim of the hummock was dissected, exposing the western and eastern sides of the outer rim of the feature. This hummock is composed primarily of compact, banded diamicton that contains sorted material (Unit 1) (Figure 5.10a). Stringers of sorted material (the largest material was pebbles), some of which were attenuated, dip toward the east at between 0-10°, which is less than the surface slope of the hummocks. Several clast fabrics taken from this hummock indicated a strong to intermediate preferred orientation (Figure 5.10a). All fabrics indicated a northwest-southeast orientation. At the base of the exposure (about 7 m above the adjacent hollow, was a deformed, grey diamicton that contained Canadian shield clasts (Unit 2). This unit was deformed internally and separated from the upper diamicton by a shear plane. The central depression of the hummock was partly filled by lacustrine and aeolian sediments with buried, poorly-developed paleosols. This unit unconformably overlaid the diamicton and winnowing of the contact is indicated by a discontinuous pebble lag.

Site #7 (UTM: 12U 481750E, 5877650N)

This site is located 250 m north of Site #8 and also is a roadcut exposing the upper 3 m of

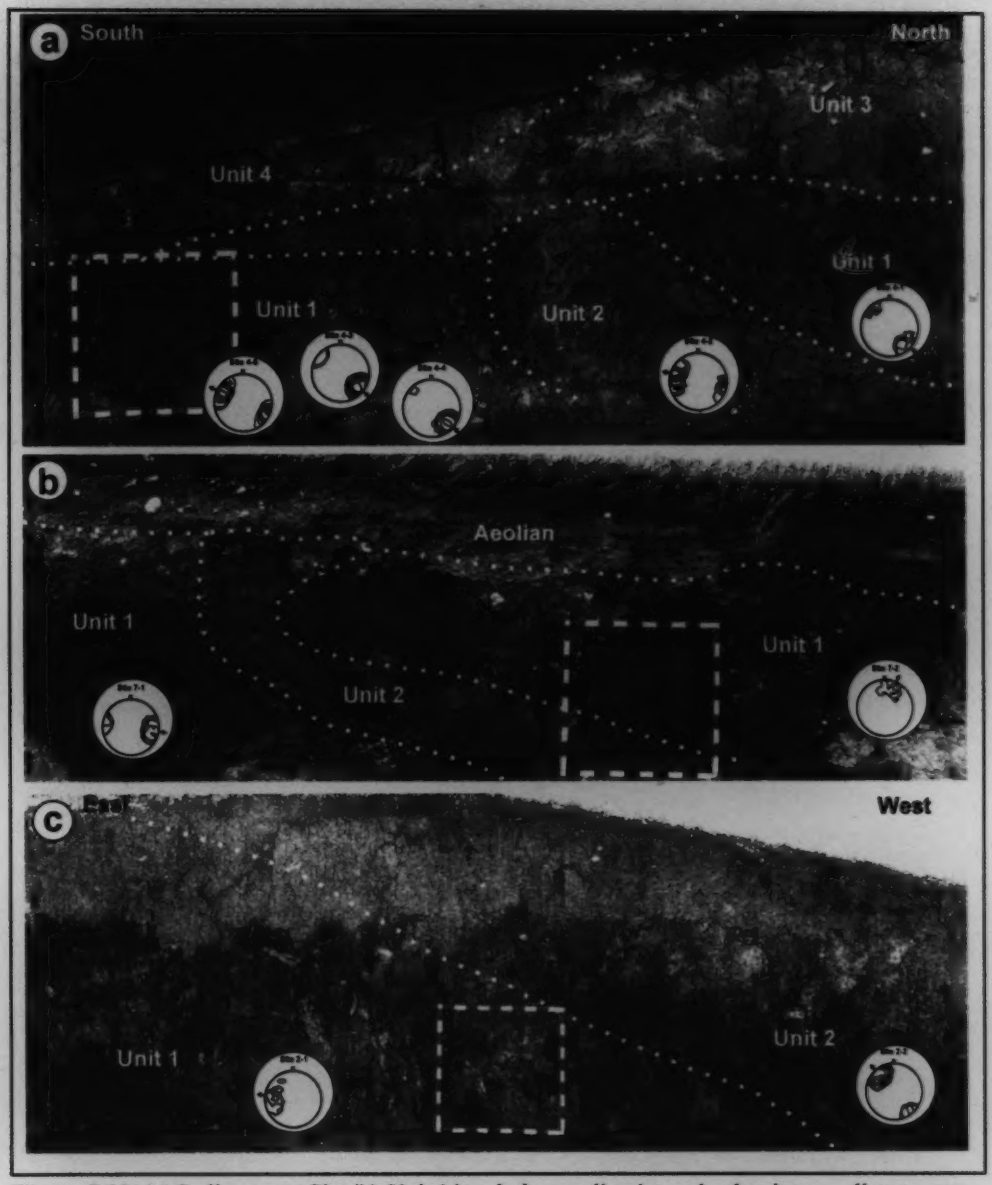

Figure 5.10: (a) Sediments at Site #4. Unit 1 is a dark grey diamicton that has intermediate to strong fabrics. Fabrics 4-3, 4-4, and 4-5 were taken from the opposing face. Units 1 and 2 are separated by a shear plane that dips to the NE. These sediments are overlain by pond and aeolian sediments (Unit 4) and a poorly compacted diamicton (Unit 3). (b) Dark grey diamicton (Unit 1) is interrupted by an overturned sand body (Unit 2). The pebbly inclusions on the right side of the photo are burrow casts. (c) Unit 1 is a banded diamicton separated from a similar diamicton (Unit 2) by a steeply dipping contact. The strength of the fabrics indicates that gravity flow and meltout probably explain the sediments.

the top of a hummock (Figure 5.10b). This exposure is capped by limited aeolian sediment and a boulder lag. The bulk of the sediment in this hummock is composed of a compact, dark diamicton (Unit 1). The diamicton is poorly sorted and has blocky structure. This diamicton is generally massive with some attenuated sand and silt stringers. These stringers of sorted sediment are seldom greater than 1-1.5 cm in thickness and are found dipping toward the northeast (on the northern side of the exposure) and are more contorted on the southwest part of the hummock. This structure is interrupted in many places with faint diapiric structures. There are many examples of folded beds (Figure 5.10b) with radically different attitudes. These indicate a complex history of deformation. The most prominent feature in this exposure is a sorted unit that is composed primarily of sand but with some pebbles and laminated silts included (Unit 2). This sediment is folded over and in places attenuated to the point of fracture. The unit is truncated at the highest point of the hummock. A few small, angular blocks of sorted material are also found close to this folded unit.

Two clast fabrics were taken from this site (Figure 5.10). These two fabrics are dramatically different, suggesting that different processes were responsible for emplacement/remobilization of the sediment (Figure 5.10b). A relatively strong orientation (S_1=0.742) was present in the northern part of the hummock and a very weak orientation (S_1=0.487) was present in the southern part of the hummock near the highly contorted sand interbeds. Both the attitude of bedding within the diamicton, and the folding in the large sorted unit, indicate that significant remobilization of the sediment on the south to southwest portion of the hummock was important. However, this did not happen on the east to northeast portion of the feature.

Site #2 (UTM: 12U 481350E, 5877100N)

Site #2 is an east-west oriented roadcut exposing the upper 2.5-3 m of a hummock. This site is located about 400 m to the southwest of Site #8 and is about 5 m lower in elevation. The profile through the hummock is asymmetrical with a steeper west to southwest slope and a dish-like hollow on the eastern side of the feature (Figure 5.10c). The western part of the exposure contains steeply (10-20°) banded diamicton (Unit 1). The banding in these diamictons is parallel to the orientation of the clasts. The dip of the banded diamictons is greater toward the centre of the feature and shallower along the western margin. These banded diamictons are overlain by a dark, massive diamicton on the western to southwestern part of the hummock (Unit 2). The contact between these two different diamictons is a shear plane. This massive diamicton is visually distinct from the

banded diamicton but the grainsize distributions do not indicate any textural difference. Small fractures are present, parallel to the bedding in the banded diamicton, whereas the massive diamicton is characterized by a columnar structure. On the eastern part of the hummock, there is an erosional contact with a minor pebble lag that is overlain by laminated lacustrine sediment. This lacustrine sediment occupies a hollow and is thickest in the lowest part of this hollow.

Distinguishing between the two distinct diamicton units is critical to interpreting the formation of this feature. The clast fabrics of these two units are very distinct (Figure 5.10c). The very strong orientation of Unit 2 (S_1=0.755) is typical for primary subglacial tills whereas the orientation of Unit 1 (S_1=0.519) is typical for flow tills (Dowdswell and Sharp 1986). The stratigraphic relationship of these two units indicates that deposition of a subglacial till postdated the gravity flow sediment.

Site #11 (UTM: 12U 476850E, 5879900N)

Two north-south oriented exposures (on each side of the road) were created by a roadcut through a hummock. Almost the entire sequence of sediment is exposed at this site and adjacent to this feature bedrock is exposed at the surface and the surrounding area is only mantled with a thin veneer of surficial sediment. This indicates that the hummock is an isolated 'island' of sediment. This hummock is part of a northwest-southeast oriented hummock tract that extends northward to Site #1. The sediment exposed in the two faces are very distinctive and illustrate how dramatic the spatial variations in sediment types may be in these features. The western exposure is composed of banded diamictons that dip increasingly steeply toward the southwest side of the feature (Figure 5.11a). This diamicton is very distinctive and similar to those found in several of the previously described sites. The larger clasts in this banded diamicton are usually oriented parallel to the orientation of the bands but in several locations such clasts are rotated into more steeply dipping attitudes (Figure 5.11b). On closer inspection, the diamicton was noted to be fissile, with the structure paralleling the orientation of the bedding. The banding radiates from the highest point of the hummock. The centre of this exposure is composed of a massive diamicton that grades into the overlying, gently dipping, banded diamicton seen in Figure 5.11a. The upper surface of this exposure is erosional as shown by the truncation of the bedding.

The eastern exposure at this site is quite different from its western counterpart considering that they are separated by only10-15 m. This exposure is characterized by near-horizontal to

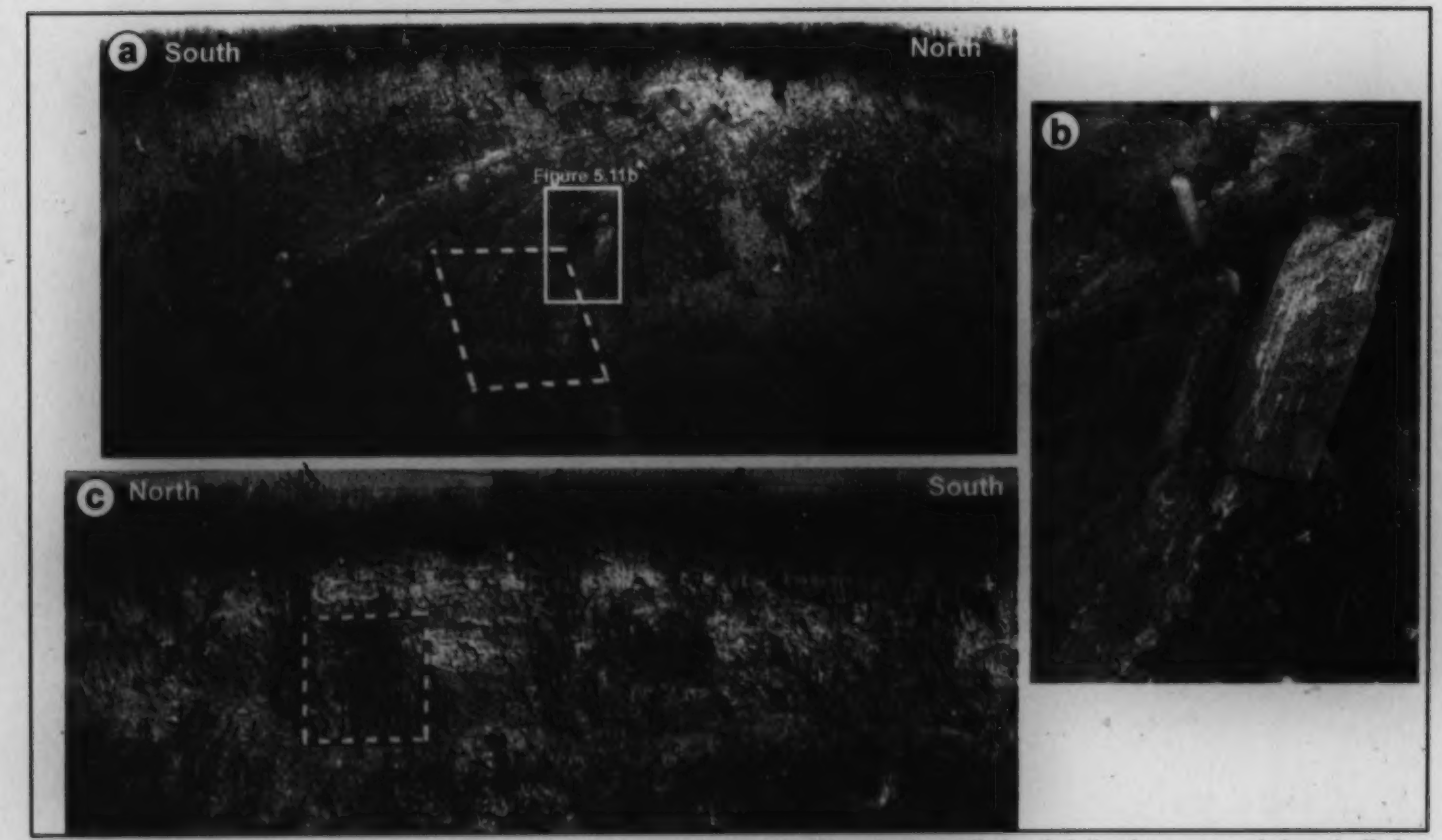

Figure 5.11: Sediments at Site #11. (a) Sediments in this face are characterized by a horizontally banded diamicton succeeded vertically by increasingly steep beds of diamicton and minor sorted sediments. The dip of these beds is generally toward the southwest. Scale is 1 m^2 (b) Close-up of one large clast indicating gravity flow deposition and rotation from the orientation of the bedding. (c) Sediments on the eastern face showing nearly horizontal beds of banded diamicton and lacustrine sediments. Lacustrine sediments are enclosed by the diamicton and there is evidence of shearing in some places.

northeast-dipping bedded diamictons and lacustrine sediments (Figure 5.11c). The lowermost unit in this exposure is a massive diamicton. This diamicton is separated from the overlying lacustrine sediment by a northeasterly dipping shear plane. These lacustrine sediments contain crushed and intact gastropod shells. Most of the delicate laminations in this lacustrine sediment are preserved, indicating only minor disturbance (Figure 5.11c). Shear planes characterize the lower and upper contacts of this unit. Along these contacts the gastropod shells are crushed into tiny fragments. The laminated lacustrine sediments are overlain by a massive diamicton with only minor silt and sand partings that are sub-horizontal or gently dipping between north to northeast. This diamicton is in turn overlain by a poorly consolidated diamicton with a higher proportion of boulders. The upper surface of this hummock has a discontinuous cobble/boulder lag.

Site #12 (UTM: 12U 466700E, 5875550N)

Site #12 is located northeast of Kinsella (Figure 5.2) and is an east-west oriented face that exposes the upper 2/3 of the hummock. This low-centred hummock is located in a field of similar forms, some of which are linked in chains (Figure 5.3e). The exposure is cut into the southern raised rim of the feature. Sediments at this site are indicated in Figure 5.12a and are arranged in a relatively simple architecture. The hummock is composed of two main units with a transitional zone. Unit 1 is a light brown diamicton, with grey mottles, that constitutes the core of the landform. This unit has very few large clasts and the matrix is only partly sorted. It contains some pods of sorted sands. The upper surface of this unit is convex-up and roughly mimics the surface form of the entire feature. Unit 2 is composed of a dark diamicton that is comparatively stony with a sorted matrix. This unit is dominated by numerous sand stringers that are sub-horizontal to steeply dipping. These sand bodies are commonly folded with the arms of the fold opening toward the top of the hummock. These two units are separated by a transition zone that is characterized by a platy structure and, like Unit 1, is poorly sorted.

Site #13 (UTM: 468600E, 5864600N)

This Site is a east-west oriented roadcut that has been excavated into a large hummock. This hummock is located south of Vernon Lake, on the interfluve between two channels that have hummocky terrain along their bottoms (Figure 5.2). In this area there are both low- and high-centred hummocks, but chains of hummocks are not common in the immediate vicinity. Boulder lags are

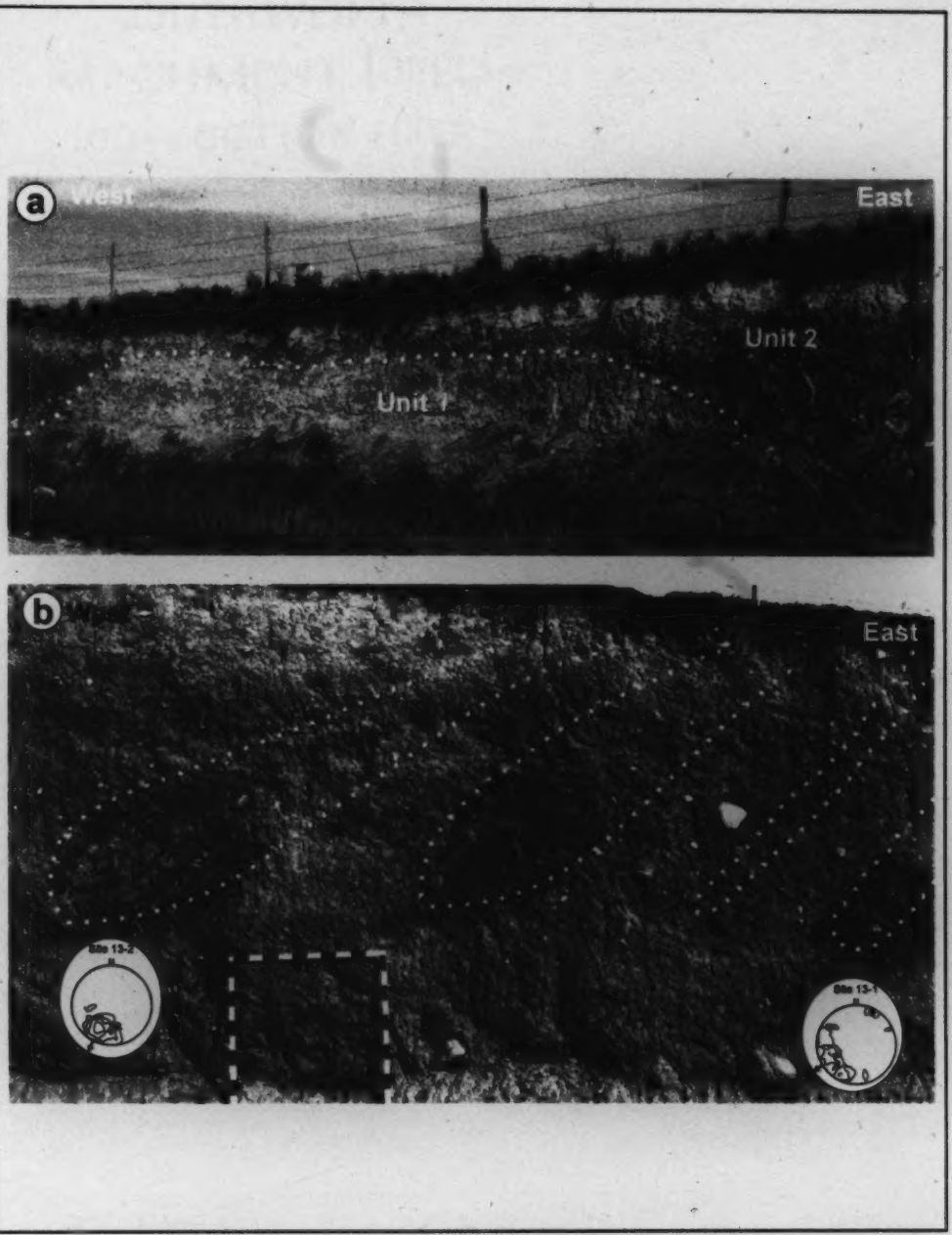

Figure 5.12: (a) Sediments at Site #12. At this site a low-centred hummock contains a core of a light-coloured diamicton with few stones. The upper unit is a dark diamicton with numerous sand stringers that dip toward the margin of the feature. (b) Sediments at Site #13. At this location a very compact diamicton contains dipping interbedded sand/diamicton. These beds dip toward the southwest, parallel to the weak fabrics.

very common on the surface of hummocks in this area and at some locations shallow gravel/boulder deposits cap the hummocks. The exposure is cut into an asymmetrical hummock (Figure 5.12b) which has one prominent peak with a secondary hump on the eastern side. Most of this hummock is composed of a dark, compact diamicton but it is interrupted by steeply dipping beds of sorted sand. These sand bodies are up to 5 cm thick and dip toward the southwest in a parallel manner. These sand beds extend to the surface of the hummock and are truncated at that point. The sand beds are different from those at Site #11 in that the attitude does not change toward the flanks of the hummock. Rather, they appear to be unrelated to the hummock morphology.

The orientation of the sand bodies is parallel to the clast fabrics (Figure 5.12b). The weak preferred orientation of these fabrics (note the fabrics were taken from the base of the section, well within the hummock) is indicative of gravity flow deposits. The clasts in the diamicton appear to be aligned parallel to the sand bodies near the sand bodies but rotated between the sand bodies. The weak fabrics, the orientation of the dipping sand bodies, and the fine texture of the matrix suggest that fluidized gravity flow was important in the emplacement of the sediment in this hummock.

Other Characteristics of Hummocks

The sedimentary characteristics of diamicton-dominated hummocks were the focus of the previous sections. However, it is important to note that in several places throughout the study area bedrock (deformed or *in situ*) occurs in hummocks. *In situ* bedrock is sometimes found to make up the core of the hummocks or to comprise the entire hummock, without any glacially derived sediment present (Figure 5.13). These bedrock-dominated hummocks are more common in local topographic lows and in channels. Hummocks within channels may be composed of glaciofluvial sediment, bedrock, and/or diamicton. This fact raises questions about how the 'channel hummocks' relate to those on higher ground. In many places the 'channel hummocks' are morphologically indistinguishable from those on higher ground in every respect except topographic setting.

Also, the character of the diamicton contained in some hummocks is not arranged in the same manner as those in the previous sections. In many locations, poorly-consolidated diamictons compose nearly all of the hummock sediment. In these situations the diamictons are horizontally banded with little if any evidence of disturbance. These hummocks are low- or higher centred. Where they are low-centred it is common to find a shallow deposit of gravel/boulders in the depression overlain by laminated (lacustrine) sediments. These hummocks are often smaller than

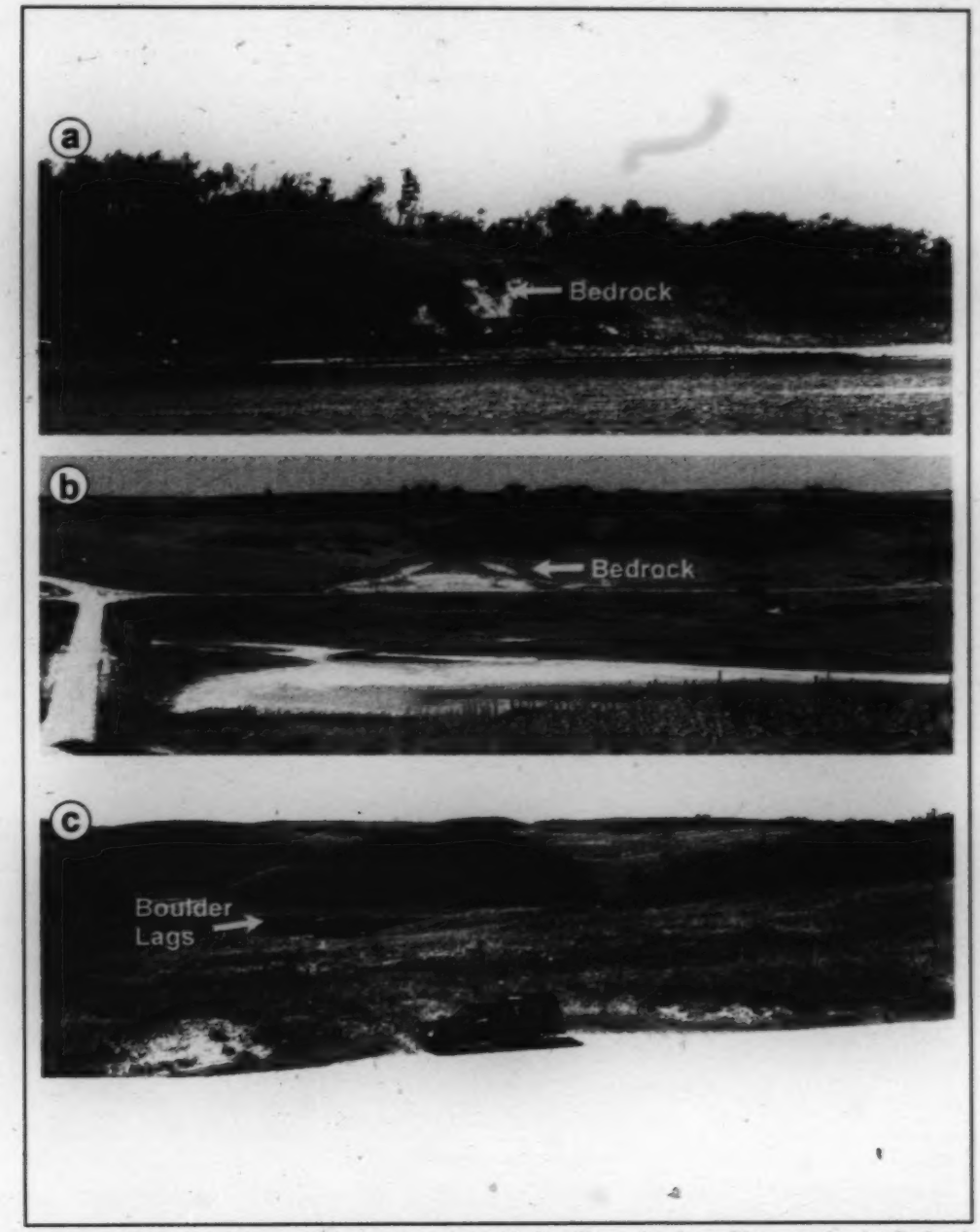

Figure 5.13: Bedrock hummocks interspersed with diamicton-dominated hummocks. (a) Bedrock hummock located in a channel east of Thomas Lake. (b) *In situ* bedrock, without any capping diamicton, located in a channel. (c) Hummocks with their bases composed of bedrock, but most of the feature is composed of diamicton. Extensive boulder lags are present in the depressions and to a lesser extent on the hummocks themselves.

those high-relief forms described above. They are found both on elevated portions of the study area, and on broad, shallow depressions in the landscape, but never on abrupt breaks in regional slope. The fact that hummocks composed of lacustrine and diamicton stacks are found most commonly on gently sloping eastern to northern slopes is critical to the interpretation of the formation of these landforms.

Gastropods and Timing of Hummock Formation

The timing and mode of HT formation are important because many researchers have used belts of HT to infer the margins of a receding ice sheet (e.g., Dyke and Prest 1987; Klassen 1989). Several of the hummocks described above (Sites #1, 8, and 11) contained crushed and intact gastropod shells. Because of the degree of preservation of these remains it was possible to radiometrically date the samples using ^{14}C. Bulk samples of intact gastropod shells were collected from Site #8 and submitted to the Geological Survey of Canada for dating. The sample was pretreated with an acid leachate to remove contamination from old carbon. This sample returned an anomalously young date of 10,000 ±120 ^{14}C years BP (GSC-6137). This date coincidently falls within the range of dates obtained by Bik (1968) and Emerson (1983) on shells found within lacustrine sediments that *superimposed* hummocky terrain in other parts of Alberta. The fact that both Bik (1968) and Emerson (1983) reported comparable dates from postglacial sediments questions the age of the sediments within HT described in this paper.

To resolve the apparent conflict between the existing information on molluscs in HT elsewhere, and the present study area, it is important to consider the context in which the shells were found. First, sediments containing these shells were always bounded top and bottom by shear planes along which the shells were crushed. Second, the enclosing sediments were always found stratigraphically **below** diamictons that are, in most cases, demonstrably subglacial tills. The interpretation of these sediments as subglacial tills will be developed further in the next section of this chapter. Third, the shells were found in the heart of the hummock sections, and in the case of Site #11 within 1-2 m of the base of the hummock. These three characteristics of the gastropod-bearing sediments preclude them from being supraglacial pond sediments, redistributed by stagnating ice (Emerson 1983).

Emerson (1983) determined that the molluscs he collected were northern species. This determination was largely based on the work of Harris and Pip (1972) and Clarke (1973). The

presence of one species found by Emerson (1983) was critical to the interpretation of the assemblage being northern. *Pisidium ferrugineum* (Prime), which was common in his assemblages, has a current range that does not extend south of the daily June isotherm of 21°C (Clarke 1973, cited in Emerson 1983), although he cautioned that the relationship between water and air temperatures may not be reliable.

The assemblage reported by Emerson (1983) is quite different from the assemblage found in the hummocks of the present study area (Table 5.2). The composite range of the species found in the hummocks is given in Figure 5.14 and indicates that this is a *southern* assemblage. The present distribution of one species (*Bakerilymnaea bulimoides* (Lea)) indicates clearly that this species could not survive in ponds dammed by stagnant glacier ice. Rather, the paleoenvironmental information obtained from these species suggests a climate similar to that of today. Thus, this information does not agree with the paleoenvironment inferred by Emerson (1983) and the ^{14}C date obtained from shells in this study. Although the ^{14}C date of 10,000 years BP corresponds with those obtained by Bik (1968) and Emerson (1983) the stratigraphic/geomorphic and paleoenvironmental contexts are quite different. In addition, it is widely accepted that the southwestern Laurentide ice sheet margin was located at the Cree Lake Moraine (northeastern Alberta and northern Saskatchewan) at 10 ka BP (Dyke and Prest 1987; Smith and Fisher 1993). Based on the geomorphic and sedimentary evidence it is suggested that the pond sediments, and the incorporated shells, were glaciotectonically placed into their present position. Therefore, the ^{14}C date of 10,000 years BP is rejected and the sediments and gastropods must be Mid Wisconsinan in age.

Table 5.2: Gastropods found in hummock sections and their habitat.

Species Identified[1]	Habitat[2]
Bakerilymnaea dalli (Baker)	lakes, ponds, small rivers, and marshes
Bakerilymnaea bulimoides (Lea)	perennial-water (lakes, ponds, small streams), vernal habitats (roadside ditches, temporary pools)
Fossaria modicella (Say)	perennial-water (lakes, ponds, small streams), vernal habitats (roadside ditches, temporary pools)
Fossaria parva (Lea)	amphibious, wet mud flats, lake shores, and river banks
Physa gyrina gyrina (Say)	present in most perennial-water habitats, and temporarily flooded swamps and pools
Physa jennessi skinneri (Taylor)	perennial-water (lakes, ponds, small streams), vernal habitats (roadside ditches, temporary pools)
Stagnicola caperata (Say)	most common in temporary-water habitats
Stagnicola elodes (Say)	found in all kinds of aquatic habitats

1. Species identification done by J. Van Es, formerly of the Biological Sciences Department, University of Alberta, Edmonton, Alberta, Canada.
2. After Clarke (1981).

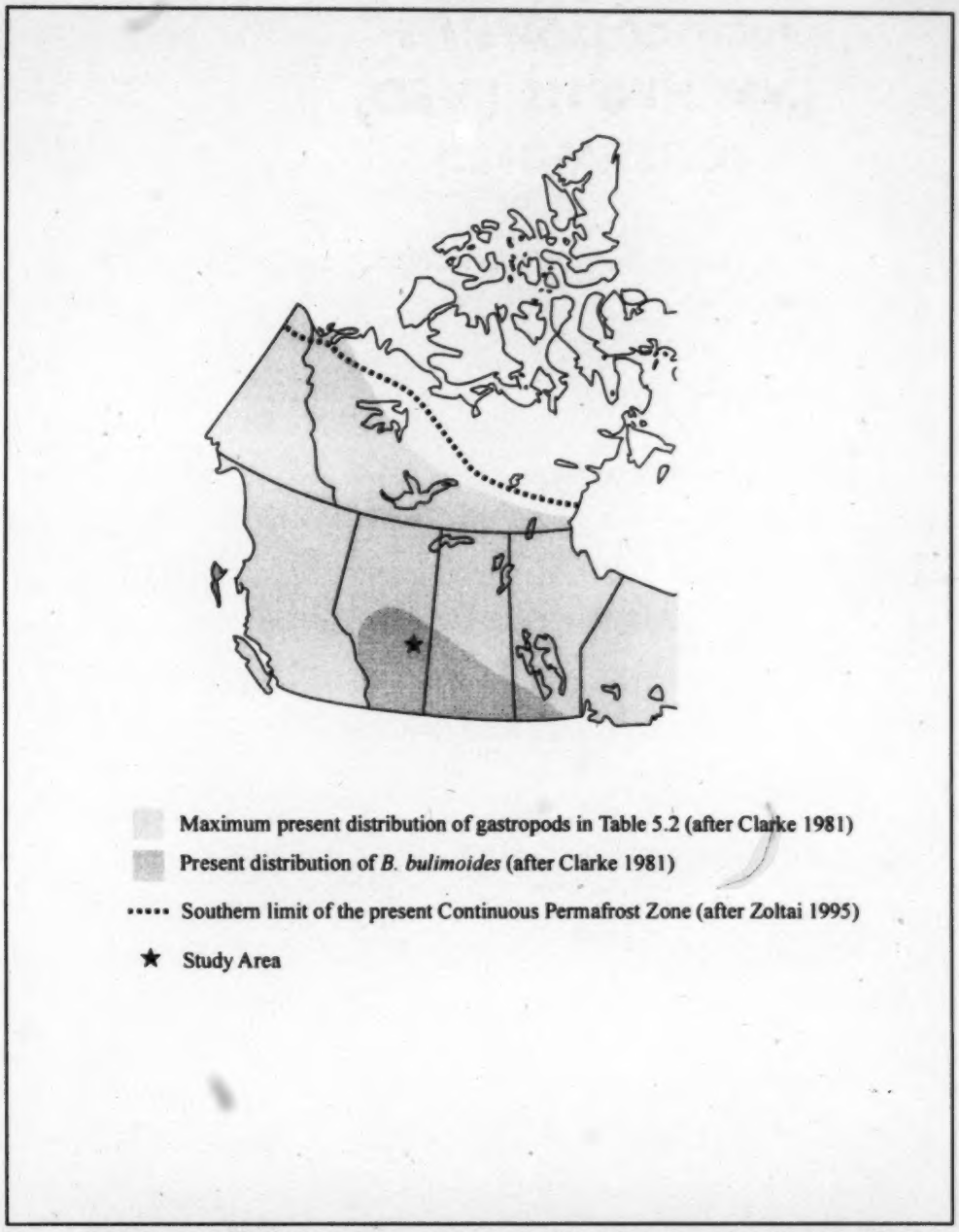
Maximum present distribution of gastropods in Table 5.2 (after Clarke 1981)
Present distribution of B. bulimoides (after Clarke 1981)
Southern limit of the present Continuous Permafrost Zone (after Zoltai 1995)
Study Area

Figure 5.14: Present distribution of gastropod species found in hummock sediments. All of the species found indicate relatively warm climates. Note the ranges are south of the southern extent of continuous permafrost. *B. bulimoides* (Lea) is dominantly a southern species and study area is near the northern extent of its range. This suggests that the climate that existed at the time of deposition of the shells was similar to, or warmer than, at present.

Summary of HT Sediments

It is apparent that the basic sediment types present in hummocks are arranged in many different ways. The presence of *in situ* bedrock in the core of hummocks requires that some depressions were formed by erosional processes. In those locations where bedrock has been displaced, glaciotectonic emplacement of the material is likely to have occurred. Large displacements of bedrock have been reported in several areas of Alberta (*cf.*, Stalker 1976) and the topography of the Viking upland is conducive to this type of entrainment (Aber et al. 1989). The potential presence of megablocks (Stalker 1976) does not necessitate a topographic expression of the features and thus it is impossible to determine their presence without detailed boreholes.

The main types of sediment in the HT are diamicton and lacustrine. As previously noted, these sediments are arranged in markedly different ways from site to site. Even though there are many different configurations, a few generalizations can be made. First, the lacustrine sediments that contain gastropod shells were always found on the northern to eastern sides of the hummocks. The shear planes that separate these sediments from the enclosing diamicton were consistently dipping toward the northeast to east. This consistency was not reflected in a preferred orientation of the hummocks themselves but, rather, was independent of the hummock morphology. These shear planes indicate that glaciotectonic stacking of sediment was important in producing the sediment pile that constitutes the HT. Second, diamictons in the hummocks were mainly composed of subglacial tills, with only a minor component of poorly-consolidated diamicton that is most appropriately interpreted as supraglacial material. The subglacial tills are present in a continuum of types from lodgement/meltout to gravity flow and, likely, deformation tills. The ubiquitous presence of sorted stringers suggests that meltout was the primary process. The absence of highly deformed diamictons indicates that widespread deformation did not occur. Although meltout was the primary mechanism, there is occasional evidence for gravity flow and slumped deposits. Third, at most every site visited the banding of the diamictons and the thrust sediments was truncated at the surface of the hummocks. Truncation of the bedding was often accompanied by surface boulder lags. Some evidence of recent slope processes obscured these truncation surfaces but this seldom extended more than 20 cm below the surface of the hummocks. Also, in many locations (but not all) bedrock is exposed in the interhummock depressions and in some places comprises the cores of hummocks. These characteristics indicate that erosion of the sediment pile was important in the formation of the hummock form.

Discussion

Several studies have drawn attention to shape continua in glacial landforms (e.g., Aario 1977). The gradual variation of hummock shapes throughout the study area suggests that the process(es) responsible for formation of the HT occurred over the entire area. The absence of end moraine segments, or any obvious break in the hummock tract, indicates that the entire area of HT formed at the same time. These characteristics suggest that the morphology-forming process(es) must have operated over the entire area. The highly variable nature of the sediment within the HT suggests that the form of individual hummocks is not necessarily related to the sedimentation process(es). The fact that all shapes of hummocks occur in different topographic settings indicates that the regional relief characteristics had little to do with the distribution of the HT.

The formation of HT has received significant attention in the literature and several theories have been developed (Table 5.1). At first glance these theories appear to be disparate, although there are common threads to each. Nearly all focus on the emplacement of sediment, whether it was by subglacial and/or supraglacial processes. The variety of different processes invoked to explain the sediment emplacement has largely been derived from studies of modern environments (e.g., Sharp 1985). Connections between HT formation in modern environments and Pleistocene landforms led to the development of the classic model of topographic inversion, via sediment redistribution, during ice stagnation (e.g., Gravenor and Kupsch 1959). The recognition that many tracts of HT are composed of flow tills and related sediments strongly supports this theory (Andersson 1998). Several researchers have recognized that marginal glaciotectonics were instrumental in stacking sediment and ice slabs during stagnation (Krüger 1996). The relationship between ice-marginal glaciotectonics and the formation of HT is often made on the linear trend of HT that is perpendicular to ice flow direction (e.g., Johnson et al. 1995). The implication of glaciotectonics in the formation of HT is important because it implies the presence of active ice rather than the classic idea of inactive ice that is slowly melting.

The recognition of glaciotectonic structures in sediment contained in the HT led to the development of different hypotheses concerning the squeezing of subglacial sediment into the hummocky forms (Hoppe 1952; Stalker 1960). Hoppe (1952) cited strong preferred clast orientations as evidence for squeezing of subglacial material into hummock shapes. This is particularly important for the present study because many of the forms described by Hoppe (1952) and Stalker (1960) are present on the Viking upland. Landforms such as 'till-filled eskers' and low-centred hummocks were central to the ideas developed by Stalker (1960). These subglacial

squeezing and traditional supraglacial letdown models have been combined into composite theories by some authors (Parizek 1969; Aartolahti 1974). More recently, Eyles et al. (1999) proposed a model of HT formation that incorporated landform continuum ideas, similar to those of Aario (1977), with the subglacial squeezing of deformable sediment hypothesis of Stalker (1960). Eyles et al. (1999) illustrated how subglacial processes (under stagnant ice), when coupled with supraglacial processes, produce some of the observed geomorphic/sedimentologic relationships. The model proposed by Eyles et al. (1999) for southern Alberta is comparable to that of Aatolahti (1974), indicating a convergence of hypotheses. The combination of these models indicates that many tracts of HT possess both subglacial and supraglacial sediments. Clearly the variety of theories on HT formation reflects site-specific characteristics that involved complex combinations of processes.

Recently, a subglacial meltwater erosion model for some HT formation has been proposed (Shaw and Ashley 1988; Rains et al. 1993; Shaw et al. 1996; Munro and Shaw 1997; Beaney 1998). In this model, hummock sediments are thought to be largely unrelated to the morphology-forming process. One of the major lines of evidence for this theory is the truncation of bedding within the hummocks. The nature of the truncated bedding is thought to be independent of the sedimentary architecture of the hummocks. The sediments within these hummocks can be undeformed and/or highly contorted. Subglacial till (including meltout), lacustrine sediments, and local bedrock are included in these hummocks in various configurations (Munro and Shaw 1997).

HT in the study area displays characteristics indicating that several processes were responsible for its formation. Shear planes on the east to northeast side of many hummocks indicate that tectonic processes were instrumental in the emplacement of subglacial till and lacustrine sediments containing gastropods. Down-glacier from these tectonic structures (in the same hummock) it is typical to find either meltout tills, with strong preferred clast orientations, or tills with fabrics indicating gravity flow processes. As previously mentioned, these lee-side tills often have a gentle dip that opposes the shear planes on the up-glacier side of the hummock. The dip of these banded tills can be toward the margins of the hummock or toward the centre. This common sequence is typical of hummocks in the area and indicates a stoss-and-lee structure to the hummocks. Stoss and lee sediment sequences were identified by Möller (1987) and he interpreted these to be formed by stagnant subglacial ice creating meltout till, subsequently superimposed by supraglacial sediment. The interpretation by Möller (1987) was specifically developed for transverse moraine but it has a striking relevance to the architecture of hummocks described in this paper. The stoss-and-lee form of the transverse moraine described by Möller (1987) also had a cap of meltout

till which buried the stoss-and-lee sequence. In many hummocks of the study area the upper sediment type is invariably a dense till, interpreted as being primarily meltout in origin. One characteristic that distinguishes hummocks from those described by Möller (1987) is that in many cases this upper meltout unit is truncated, thereby exposing sediments lower in the feature.

As previously mentioned, the hummocks in the study area do not always align with the glacier flow direction indicated by the shear planes and lee tills. Often, the long axis of an individual hummock is oriented perpendicular to this direction. This is particularly true for Sites #4, 7, 8, and 11. Conversely, Site #1 has a long-axis orientation perpendicular to this inferred flow direction. These observations are somewhat problematic considering the transverse nature of the landforms which would be expected if glaciotectonics were responsible for emplacing the sediment and creating the final hummock morphology. Also, because several hummocks are composed of *in situ* bedrock, the process responsible for emplacing the glaciogenic sediment appears to be of little importance in the formation of their final morphology. Thus, in reconstructing the paleoenvironments responsible for formation of the HT in this area it is important to investigate how the glaciotectonic, meltout, and morphology-forming processes link together.

On the basis of the observations presented in this paper the following events are inferred to have created the HT that superimposes the Viking upland:

1. The preglacial landscape was eroded by fluvial systems. The Viking upland was created by the incision of the Wainwright and Vermilion river systems, thereby leaving the upland as a major plateau in the area.

2. Prior to the onset of glaciation in the area, and prior to the related Late Wisconsinan cooling, shallow lakes and ponds were the home of the gastropods now found within the hummock sediments. These ponds were unlikely to have been deeper than 2-4 m (based on the lack of deep water-tolerant species). The ponds were most probably active during part of Mid Wisconsinan time.

3. Glacial onset was accompanied by localized glaciotectonics along the margin. These translocations of sediment were focused on the up-glacier facing escarpments.

4. Overriding of the preglacial landscape by the Laurentide ice sheet initiated a complex temporal sequence of thermal conditions at the base of the ice. Freezing and thawing are necessary for accretion of sediment into the base of the ice. Polythermal conditions that vary both spatially and temporally would have enabled sediment to be accreted and then deposited (*cf.*, Shaw 1994). At this time combinations of previously glaciotectonically displaced sediment and subglacial ice/sediment would have been emplaced. The stoss-and-lee nature of many hummocks in the area suggests the probability of longitudinal concentrations of debris, both subglacially and englacially. The entrainment of sediment, and subsequent deposition, must have involved

fluctuations of the thermal conditions of the glacier, at least locally.

5. Following the emplacement of the sediment under changing thermal conditions, the ice stagnated, depositing meltout till that is observed as gradations between some of the diamictons.

6. After the deposition of this meltout till the subglacial environment would have had undulations that partly reflected the underlying bedrock topography and partly the spatially variable deposition of glaciogenic sediment.

7. Erosion of the undulatory glacier bed would have been accomplished by a shallow, short-lived outburst of stored subglacial water that differentially eroded the glacier bed. The local variations in sediment thickness concentrated erosion in the topographic lows, thereby setting up a positive feedback. This erosion was focused in the lower areas in the region thereby stripping much of the sediment off these areas. Only minor erosion occurred in some areas because the architecture supports the idea that the morphology was initiated by the differential deposition of sediment. The erosion below the glacier was responsible for developing bedrock hummocks in hummock tracts, and within channels, and accentuating subglacial channels (Chapters Three and Four). Boulder lags attest to this fluvial erosion. The concentration of boulders in most 'kettles' indicates enhanced erosion of those depressions.

8. The erosion was short-lived and relatively minor in comparison to the main flood paths (Chapter Two). The initial sheetflow was quickly succeeded by partly channelized flow that carved/modified subglacial channels, such as those in the Kinsella area. After the discharge declined the ice settled back to its bed. Much of the englacial debris had been removed from the base of the ice, although there are minor (< 20 cm thick) meltout tills superimposed on the truncation surfaces, indicating that not all sediment was removed.

9. After the meltwater event the ice stagnated, only slightly modifying some the hummocks. Eskers were formed at this time and are found on top of, and truncating, HT.

10. Postglacial modification of the HT was minimal and involved minor slumping and slope processes, plus some aeolian sediment-mantling.

Conclusions

The formation of HT has been attributed to several different, but not necessarily mutually exclusive, processes. Most models of HT formation have focused on supraglacial and subglacial sediment being deformed or deposited into the hummock forms. There is significant evidence that **some** HT was formed by erosional processes. Because of the complexity of subglacial environments there are multiple sediment types and sediment architectures. The fact that there are so many different hypotheses regarding the formation of HT attests to this complexity. The fact that *in situ* bedrock and deformed/tectonized glacial sediments have the same morphologic expression suggests that classic models of HT formation by stagnating ice are inadequate. Rather, this fact indicates that

a process that is unrelated to the deposition of the sediment must be responsible. The truncation of the bedding indicates that erosion best explains these characteristics. The fluid dynamics of an unstable sheetflow, bounded on top by ice and beneath by deformable and/or consolidated sediment/bedrock, are poorly understood but integral to this hypothesis.

In conclusion, the evidence from the Viking upland in east-central Alberta indicates that differential meltwater erosion of subglacial materials formed the hummocky terrain. The erosion is thought to have been restricted because glaciotectonic processes and thermal conditions at the base of the ice caused spatially varied deposition that was only accentuated by the erosion. Relatively modest erosion of some tracts of hummocks, particularly on higher ground, explains the relative height of the hummocks and also the morphology. The subdued nature of hummocks on local topographic lows would then be the result of greater amounts of erosion and superimposition by proglacial lacustrine sediments.

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CHAPTER SIX: SUMMARY OF FINDINGS AND FUTURE RESEARCH OBJECTIVES.

Questions posed by this thesis

This thesis focused on the formation and modification of landforms in part of the Viking Moraine in east-central Alberta. In Chapter One, four questions were posed which were critical to the understanding of landscape development in the area:

1. What process(es) were responsible for the large-scale landscape unconformities in east-central Alberta?
2. What environment(s) are represented by meltwater channels including the 'stream trenches'?
3. What depositional environment(s) are represented by the Kinsella Glaciofluvial Complex?
4. What was the formative environment(s) of the hummocky terrain?

Thesis Summary

Chapter Two focused on the relationship between areas with minimal glaciogenic material overlying bedrock, and associated linear landforms. Several studies have proposed that linear landforms are formed by fast-moving ice, preferentially excavating a deformable substrate (e.g., Boyce and Eyles 1991; Hart 1995). In addition, Patterson (1998) has proposed that ice streams flowed through Alberta producing the landforms found within the Torlea Flats and connected areas. The evidence presented in this thesis does not support the claims of Patterson (1998) and strongly supports the conclusions of Rains et al. (1993) and Shaw et al. (1996) that catastrophic outbursts of subglacial water were largely responsible for formation of the landscape. Regional-scale evidence for diversion and deflection of waning subglacial flood water was placed into context with late-stage channelized erosion. The combination of diversion, deflection, and channelization is central to the contention that subglacial sheetflows are unstable and are quickly channelized (Walder 1982; Brennand and Shaw 1994; Sjogren and Rains 1995). In addition to invoking meltwater erosion, Chapter Two also investigated the influence of tectonic predesign (Eyles et al. 1997) in controlling the distribution of erosion and how it is represented in the landscape. Thus, the intimate linkage between orogenic processes, preglacial topography, and subglacial processes was established and suggested the interaction between several different but interrelated processes.

In Chapter Three, meltwater channels that cross-cut the Viking Moraine were investigated

for their morphology and sedimentary characteristics. The formation of the channels fit into the generalized regional model of subglacial erosion proposed in Chapter Two. It was concluded that the channels were formed as tunnel channels during the waning stages of the subglacial flood event that scoured the Torlea Flats. Linkages between the scoured Torlea Flats and channels in the main part of the Viking Moraine indicated that they were formed at the same time and by the same set of processes. The morphology, sediments, and continuity with related landforms indicated that the glaciofluvial channels were not formed as glacial spillways (e.g., Kehew and Lord 1986) or as 'stream trenches' that were filled with slumped glacial sediment (Gravenor and Bayrock 1956; Parizek 1969). Also, the integrated nature of most of the channel subsystems indicated that they formed catastrophically as channels (Brennand and Shaw 1994) rather than by steady-state erosion (e.g., Boulton and Hindmarsh 1987).Two main lines of evidence indicating a subglacial origin are the facts that several channels traverse bedrock-controlled highs and some are superimposed by subglacial eskers. Investigation of the channel morphology and sediments revealed that the subglacial topography produced by the preglacial topography and glaciotectonic processes were important in the routing of the waning stages of water over the Viking Moraine. Some of the channels were initially formed during glacier onset and were subsequently enhanced by subglacial meltwater action, thereby substantiating a polygenetic formation of some the channel segments.

In Chapter Four the Kinsella Glaciofluvial Complex (KGC) was investigated with the purpose of determining the formative environment. In the process of reconstructing the paleoenvironment, it was necessary to investigate the inlet channels and their sedimentary characteristics. As noted in Chapter Three, many of the channels that converge on the KGC are demonstrably subglacial and primarily erosional. The KGC is located in a broad bedrock depression that forms one of the low areas in the undulatory surface of the Viking upland. Because of its topographic setting it was a focus of sedimentation in preglacial, proglacial, glacial, and postglacial environments. Because of the lack of multiple tills in the area (*cf.*, Warren 1954) and the recent contention that only one glaciation has influenced central Alberta (Liverman et al. 1989; Young et al. 1994), the sedimentary sequence was inferred to represent a single nonglacial, glacial, nonglacial 'cycle'. On the basis of stratigraphic and geomorphic evidence, it was concluded that the sediments in the KGC recorded several erosional/depositional processes nearly all of which occurred subglacially. The main depositional event was associated with the waning flood produced large gravel/boulder dunes through the KGC. The formation of the KGC was therefore dependent on the

preglacial topography and its interaction with waning flood discharges.

Chapter Five focused on the formation of hummocky terrain in the study area. The hummocky terrain was found to be dominated by subglacial tills, most of which were meltout in origin. The presence of bedrock-dominated hummocks, interspersed with diamicton-dominated forms, when coupled with pervasive erosional surfaces of the hummocks indicated that the hummocks were erosional. The spatial distribution of glaciotectonized sediments within the hummocks indicated that there was an intimate linkage between the subglacial topography (and hence the bedrock topography) and the glacial dynamics. The glaciotectonically stacked material was primarily found in areas that sloped toward the east and northeast. These stacked sediments originated during glacial onset and subglacially, not along a stagnating front (Krüger 1996). The origin and arrangement of the diamicton contained in the hummocks were reminiscent of sedimentary sequences found in Sweden (Möller 1987) for transverse moraine ridges. This pronounced stoss-lee arrangement was not ubiquitous but common in the study area. The classic ice stagnation theory of hummocky terrain formation (Gravenor and Kupsch 1959) was not supported by the nature of sediments in this area. Instead, the sediment/landform associations indicated that a complex interaction between ice advancement, overrun, and subsequent erosion best explained the observed features. The hummocky terrain in this area is adequately explained by models given by Rains et al. (1993) and Munro and Shaw (1997) although the hummock morphology, in this area, was not entirely due to erosional processes. In this case the meltwater erosion enhanced subglacial undulations that were already present.

General Conclusions

Several general conclusions can be made based on the findings of this thesis:

1. The present landscape is largely inherited from the preglacial topography. The geomorphic impact of glaciation was minimal, depositing only a thin veneer of glaciogenic sediment and locally displacing the underlying bedrock.

2. The interaction between ice sheet and subglacial topography was responsible for complex thermal conditions that resulted in spatially variable glaciotectonics, till deposition, meltwater storage, and meltwater routing.

3. Glacial landscape development in east-central Alberta was largely terminated by an enormous outburst of subglacial meltwater that created the landscape unconformities noted in Chapter Two. The interaction between the ice surface and glacier bed topography was time-dependent; first the routing of the meltwater was primarily controlled by the ice surface slope which was

succeeded by an increasingly important influence of the bed topography. In the final stages of this meltwater flood the driving hydraulic pressure was only capable of forcing water over saddles in the subglacial topography, thereby rerouting the water. Therefore, the unstable water sheets were rapidly channelized and rerouted. Because of this rapid transition between sheetflow and channelized flow, the upper portions of the Viking upland were only slightly modified, whereas the lower parts of the terrain were areas of enhanced erosion followed by greater deposition.

4. During deglaciation many of the channels that were formed subglacially were reoccupied and further enhanced. This did not always occur but does explain the difficulty in distinguishing between subglacial and subaerial channel networks.

Future Research Objectives

The landform assemblages present in the study area indicate that temporal variations in the thermal conditions of the Laurentide ice sheet, and the late-stage release of stored water, explain the landforms present in this part of the Viking Moraine. Several intriguing questions arise from this thesis. First, the regional diversion of subglacial meltwater, alluded to throughout the thesis, converges on a large shallow depression that begins abruptly on the south and southeast side of the Battle River. This large depression has been mapped as dominantly lacustrine and glaciolacustrine sediment (Shetsen 1990), although in many places eskers are stratigraphically above the lacustrine sediments. This lacustrine basin is directly connected to the 'stream trenches' (Gravenor and Bayrock 1956) and intimately associated with several suites of glaciotectonized terrain. How this basin relates to the glaciofluvial erosion presented in this thesis is critical to understanding the processes involved and will be a focus of future research. Second, the Battle River truncates the connection between the lake basin to the southeast and the glaciofluvial channels to the northwest. The Battle River has been implicated in the drainage of Glacial Lake Edmonton (Gravenor and Bayrock 1956). The present path of the river crosses at least one significant topographic divide in the study area, and this fact precludes a subaerial initiation. Was the Battle River initiated as a tunnel channel that was subsequently utilized by the drainage of proglacial lakes? If not, how was it formed because it is inconsistent with the preglacial drainage indicated by Pawlowicz and Fenton (1995)? Third, how do the moraine plateaux fit into the model presented in this thesis? Similar features have been ascribed to ice wastage/lake infills (Ham and Attig 1996), and also differential meltwater erosion (Rains et al. 1993). The internal composition/arrangement is critical to the model presented in this thesis and will be the subject of future research.

The subglacial sheetflood(s) hypothesis originally proposed by Shaw (1983) faces considerable skepticism in the scientific community even though a growing body of geomorphic/sedimentologic evidence supports the idea. One important argument against the hypothesis has been the lack of evidence for a storage reservoir capable of supplying the meltwater. Generally, two storage reservoirs have been proposed: (1) subglacial lakes (Shaw et al. 1989), and (2) supraglacial lakes (Shaw 1996). The presence of lakes under the polar Antarctic ice sheet (e.g., Oswald and Robin 1976; Dowdswell and Siegert 1999) supports the probable existence of lakes beneath more temperate ice sheets such as the Laurentide. The topographic setting and spatial extent of subglacial lakes is very poorly understood. Munro-Stasiuk (in press) proposed the presence of a subglacial lake in southern Alberta which likely connected to the same subglacial flood that stripped the Torlea Flats of sediment, forming the large-scale linear landforms (Chapter Two). The proposition of many small subglacial lakes draining simultaneously is an interesting prospect because it removes the necessity of a single, large reservoir. The idea of numerous small lakes is supported by the recent work of Dowdswell and Siegert (1999). Defining the existence and spatial extent of these lakes in other areas of the Laurentide ice sheet is an intriguing prospect for future studies.

Another important aspect of the flood hypothesis is the potential linkage with extraglacial areas. The interactions with proglacial lakes is particularly intriguing because the release of subglacial water could act as a potential trigger for the catastrophic drainages described in numerous papers (e.g., Bretz 1969; Kehew and Lord 1986; Fisher and Smith 1994; Kehew and Teller 1994). The input of subglacially stored water into proglacial lakes has recently been proposed by Shaw et al. (in press) as a potential trigger for the Glacial Lake Missoula floods in Washington state. In addition, it has also been proposed that reversed drainage from proglacial lakes into subglacial reservoirs may have occurred (Shoemaker 1992). The potential interactions between such reservoirs has important implications for the stability and dynamics of the ice sheet. When coupled with the presence of deformable substrates the destabilization of the ice sheet by hydrologic processes may help to explain the episodic surging of the Laurentide ice sheet during deglaciation that has been reported by many researchers.

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APPENDIX 1: PALEOCURRENT AND FABRIC DATA USED IN CHAPTER FOUR

Site #6

Dip azimuth of cross-beds

205, 190, 151, 140, 200, 166, 178, 147, 156, 164, 144, 182, 204, 212, 265, 201, 175, 168, 241, 225, 216, 235, 244, 230, 250

*Clast Fabric for **Diamicton** in lower pit (azimuth dip)*

82 6, 48 22, 45 3, 82 28, 136 34, 49 28, 105 34, 125 28, 60 29, 218 30, 211 5, 122 28, 112 36, 45 26, 55 22, 44 41, 40 7, 242 5, 288 11, 162 40, 243 35, 258 12, 324 31, 65 31, 235 18, 10 46, 146 53, 76 14, 35 24, 246 7

Site #8

Dip azimuth of imbricate gravels

292, 288, 249, 264, 257, 280, 316, 256, 322, 335, 41, 60, 246, 351, 321, 256, 330, 335, 287, 234, 281, 231, 353, 319, 341, 315, 327, 322, 22, 318

Dip azimuth of cross-beds

54, 25, 34, 103, 55, 76, 160, 51, 70, 80, 145, 153, 21

Site #9

Dip azimuth of imbricate gravels

340, 230, 180, 190, 188, 178, 162, 166, 229, 173, 143, 170, 204, 212, 205, 224, 181, 164, 222, 169, 177, 183, 220, 211, 181, 204, 236, 219, 251, 208

Dip azimuth of cross-beds

185, 154, 127, 16, 23, 5, 94, 80, 92, 340

Site #10

Dip azimuth of cross-beds

112, 83, 85, 121, 124, 92, 119, 105, 102, 74, 80, 110, 90, 104, 135, 111, 82, 88, 79, 84, 95, 92, 87, 100, 112, 70, 78, 77, 96, 81, 15, 94, 77, 100

Site #11

Dip azimuth of cross-beds (eastern pit)

35, 4, 32, 23, 26, 41, 47, 98, 46, 77, 42, 66, 4, 69, 72, 56, 19, 50, 53, 55, 56, 72, 103, 78, 66, 30, 71, 102, 21, 20, 22, 28, 19, 26, 12, 3, 1, 23, 296, 327, 340, 311, 334, 340, 359, 1, 22, 16, 21, 346, 42, 45, 8, 10, 35, 8, 34, 20, 320, 310, 312, 29, 65, 43 ,30, 8, 352, 23, 112, 116, 119, 111, 101, 132, 107, 70, 87, 154, 126, 60, 79, 139, 81, 102, 118, 130, 104, 88, 85, 139, 139, 144, 78, 91, 106, 118, 133, 99, 89, 135, 95, 138, 91, 89, 90, 101, 123, 116, 95, 129, 72, 80, 74, 98, 65, 83, 85, 105, 73, 121, 77, 108, 124, 144, 118, 94, 86, 78, 82, 73, 114, 96, 104, 77, 118, 96, 124, 65, 83, 64, 80, 70, 59, 87, 73, 108, 75, 32, 46

Dip azimuth of cross-beds (western pits)

347, 353, 2, 4, 8, 358, 94, 1, 3, 5, 22, 35, 42, 73, 21, 88, 70, 84, 60, 80, 54, 41, 35, 133, 78, 59, 52, 40, 12, 356, 17, 78, 55, 100, 21, 50, 91, 93, 52, 100, 45, 48

Site #12

Dip azimuth of cross-beds

42, 128, 71, 111, 131, 150, 208, 146, 139, 71, 168, 133, 121, 125, 102, 153, 159, 165, 149, 126, 162, 160, 162, 155, 161, 82, 155, 171, 166, 175, 154, 164, 140, 118, 98, 162, 130, 160, 163, 80, 166, 358, 86, 192, 158, 169, 140, 125, 105, 158, 121, 115, 127, 106, 90, 98, 156, 124, 146, 153, 171, 144, 162, 90, 164, 174, 133, 144, 185, 134, 143, 163, 116, 125, 177, 146, 182, 168, 142, 134, 115, 163, 192, 149, 163, 175, 161, 167, 155, 186, 119, 139, 151, 127, 132, 145, 160, 155, 161, 133, 134, 160, 140, 142

Site #13

Dip azimuth of cross-beds

40, 60, 359, 31, 324, 354, 122, 135, 125, 142, 74, 55, 84, 118, 250, 115, 150, 146, 167, 169, 149, 148, 127, 158, 168, 182, 177, 142, 144, 160, 158, 164, 271, 150, 152, 100, 219, 207, 233, 175, 216, 197, 260, 203, 256, 107, 167, 118, 173

APPENDIX 2: FABRIC DATA (AZIMUTH DIP) USED IN CHAPTER FIVE

Fabric 0

320 12, 303 7, 335 9, 329 21, 80 5, 132 3, 246 26, 142 16, 315 3, 68 37, 344 10, 164 18, 263 34, 60 11, 72 24, 315 7, 304 48, 191 28, 17 22, 104 8, 300 13, 121 5, 119 6, 322 8, 307 18, 207 20, 219 34, 330 5, 298 12, 354 2, 321 4, 360 3, 275 21

Fabric 1-1

286 37, 282 14, 298 29, 293 15, 269 6, 279 34, 225 27, 293 14, 298 28, 286 8, 4 12, 292 2, 346, 34, 285 40, 310 8, 250 33, 275 5, 270 24, 249 25, 208 22, 286 11, 281 19, 289 15, 267 7, 274 9

Fabric 1-2

117 20, 237 40, 264 35, 112 14, 106 8, 209 5, 266 42, 234 27, 240 35, 65 14, 230 32, 266 12, 237, 30, 225 10, 284 39, 257 25, 204 40, 200 32, 237 20, 220 42, 297 50, 288 3, 271 12, 290 14, 210 8

Fabric 1-3

230 8, 268 9, 272 10, 207 24, 251 3, 253 7, 210 18, 56 13, 248 8, 187 18, 191 42, 224 33, 50 2, 205 14, 243 7, 232 22, 205 6, 207 15, 303 12, 32 16, 65 18, 221 9, 225 24, 227 17, 59 43

Fabric 2-1

261 16, 233 26, 48 2, 191 36, 349 4, 270 30, 98 2, 258 16, 253 25, 256 12, 295 38, 253 21, 181, 22, 294 10, 156 20, 264 30, 274 60, 242 25, 313 4, 302 38, 82 24, 5 33, 147 21, 315 61, 306 26, 345 22, 179 18, 176 23, 328 26, 200 17

Fabric 2-2

330 21, 327 8, 234 12, 335 21, 150 7, 166 26, 157 21, 307 15, 279 52, 315 1, 323 45, 309 28, 357, 42, 324 15, 325 19, 320 48, 174 13, 275 23, 330 6, 315 20, 270 3, 317 25, 298 7, 300 12, 165 24, 301 21, 299 54, 322 9, 132 2

Fabric 3-1

46 49, 59 7, 357 2, 222 34, 102 20, 62 23, 70 23, 98 36, 147 30, 94 37, 49 18, 137 31, 120 13, 103 16, 92 21, 115 29, 153 34, 67 47, 81 23, 183 4, 229 29, 99 48, 76 25, 24 45, 217 8, 224 48, 121 73, 96 28, 79 37, 25 77

Fabric 3-2

270 7, 198 13 315 59, 335 52, 317 19, 312 31, 301 45, 210 26, 308 9, 324 7, 273 6, 192 12, 316 20, 335 36, 175 4, 341 32, 330 36, 177 1, 334 5, 347 2, 338 17, 325 12, 73 22, 204 4, 212 14, 187, 19, 46 26, 232 15, 188 17, 330 26

Fabric 4-1

143 13, 118 44, 123 31, 143 1, 133 24, 162 16, 149 40, 116 28, 72 24, 19 12, 156 16, 161 10, 132 62, 133 13, 136 3, 290 42, 320 25, 133 13, 326 3, 257 17, 216 18, 270 15, 267 11, 290 21, 204 10, 236 17, 68 30, 50 33, 346 12

Fabric 4-2

92 4, 250 16, 328 14, 303 8, 117 10, 90 2, 261 33, 293 10, 215 54, 316 22, 304 20, 293 31, 246 54, 52 9, 221 21, 350 18, 309 9, 250 22, 110 13, 101 3, 308 4, 313 19, 230 22, 266 5, 273 7, 269 18, 265 24, 295 9, 322 24, 270 3

Fabric 4-3
247 25, 160 29, 312 11, 124 10, 114 52, 128 21, 113 36, 134 24, 115 6, 126 12, 127 9, 132 16, 118 23, 162 7, 119 6, 128 17, 306 15, 236 25, 305 2, 107 26, 161 29, 102 27, 126 19, 140 28, 136 7, 47 20, 149 24, 150 13, 105 32, 109 12
Fabric 4-4
132 18, 140 25, 222 37, 60 19, 221 45, 117 16, 154 30, 310 28, 150 16, 124 21, 100 27, 214 7, 121 32, 148 28, 161 13, 142 8, 204 25, 257 42, 240 21, 125 5, 120 11, 132 21, 140 34, 132 20, 290 44, 110 35, 147 15, 138 50, 123 50, 262 45
Fabric 4-5
25 10, 290 4, 93 7, 298 10, 304 12, 315 11, 280 5, 318 6, 263 42, 310 2, 123 35, 313 6, 284 4, 291 2, 358 8, 274 40, 310 5, 285 4, 276 25, 308 9, 285 14, 310 17, 290 11, 134 28, 224 36, 287 14, 220 5, 145 12, 270 9, 324 40
Fabric 5
194 24, 49 36, 304 17, 37 26, 24 21, 64 23, 20 14, 5 6, 27 20, 358 20, 31 24, 73 23, 27 36, 50 21, 170 58, 210 31, 112 10, 218 20, 40 28, 44 13, 115 22, 63 28, 60 31, 58 35, 52 15, 71 24, 101 23, 77 26, 25 15, 3 20, 347 17
Fabric 6
148 3, 192 20, 220 32, 26 6, 359 8, 23 4, 227 38, 2 6, 192 16, 210 14, 204 25, 16 5, 343 22, 85 15, 145 28, 310 8, 172 38, 155 2, 336 7, 52 28, 55 70, 49 12
Fabric 7-1
60 11, 106 9, 124 22, 94 11, 89 17, 6 5, 97 15, 76 21, 99 51, 101 14, 105 35, 93 20, 138 11, 25 9, 121 5, 96 31, 38 17, 145 14, 95 14, 101 12, 92 18, 24 33, 119 14, 81 4, 203 61, 101 14, 122 7, 99 19, 265 10
Fabric 7-2
291 11, 4 10, 50 14, 62 15, 9 45, 327 66, 222 17, 23 7, 55 24, 3 46, 335 13, 77 26, 291 52, 356 27, 130 33, 336 3, 275 32, 287 2, 40 24, 222 22, 189 41, 52 32, 344 12, 3 31, 122 33 95 30, 142 48, 20 33
Fabric 8-1
280 3, 85 46, 273 14, 83 24, 115 21, 42 5, 110 27, 250 16, 45 15, 95 42, 232 4, 82 5, 100 53, 29 30, 356 27, 268 5, 260 14, 262 24, 68 10, 71 3, 76 8, 264 7, 311 4, 142 6, 110 36, 135 22, 122 43, 153 21, 103 35, 308 16
Fabric 8-2
348 22, 67 40, 101 25, 324 32, 317 46, 55 52, 45 42, 62 25, 40 45, 48 30, 94 53, 230 22, 90 3, 10 40, 52 28, 323 29, 67 35, 281 33, 316 15, 320 17, 221 5, 322 45, 42 18, 107 12, 63 45, 319 42, 245 40, 56 11, 226 12, 295 20
Fabric 8-3
82 20, 14 50, 170 32, 135 27, 186 17, 278 26, 281 4, 65 27, 330 12, 276 18, 71 35, 130 3, 292 19, 344 32, 277 16, 116 14, 122 5, 146 24, 319 12, 30 15, 288 19, 84 1, 285 14, 296 21, 132 25, 340 16, 297 15, 50 8, 142 21
Fabric 13-1
182 4, 221 11, 196 18, 133 5, 277 22, 132 31, 193 13, 181 10, 216 47, 136 9, 322 4, 291 49, 281 26, 255, 15, 298 24, 150 3, 174 5, 232 3, 272 39, 221 31, 214 15, 296 9, 264 3, 93 8, 188 5, 237 5, 235 14, 240 13, 38 8, 8 17, 263 17
Fabric 13-2
186 37, 328 9, 360 38, 235 37, 153 13, 141 35, 217 42, 203 19, 242 47, 223 72, 224 45, 177 11, 208 56, 17 6, 242 23, 195 30, 331 28, 191 32, 304 30, 75 24, 290 14, 166 8, 195 11, 205 15, 297 24, 177 36, 244, 55, 232 15, 296 3, 221 3

Fabric 14
343 6, 44 2, 40 8, 186 3, 32 2, 121 30, 159 24, 38 36, 66 8, 200 10, 196 1, 37 34, 127 8, 222 10, 14 3, 40, 13, 67 4, 118 12, 2 7, 329 10, 53 30, 201 14, 252 7, 51 6, 85 12, 170 11, 150 9, 45 5, 63 26, 7 65
Fabric 15
273 26, 265 15, 106 14, 35 6, 152 37, 23 40, 245 5, 38 3, 7 30, 274 20, 10 13, 230 24, 235 3, 263 3, 298, 44, 246 43, 240 15, 245 38, 262 33, 30 16, 240 32, 234 14, 263 7, 242 10, 247 31, 32 4, 183 18, 226 15, 235 3, 254 36
Fabric 17-1
132 21, 160 4, 227 26, 195 37, 360 1, 4 33, 82 40, 56 54, 355 35, 99 30, 230 9, 211 24, 214 28, 276 17, 357 18, 360 56, 332 27, 196 8, 12 40, 257 10, 25 48, 257 13, 8 26, 225 6, 286 6, 341 49, 18 35, 50 20, 326 34, 55 36
Fabric 17-2
338 30, 47 5, 165 14, 357 11, 127 62, 264 5, 278 12, 209 28, 194 42, 203 43, 26 3, 121 42, 210 45, 189, 51, 91 23, 165 23, 139 10, 337 16, 171 3, 198 5, 140 21, 123 15, 244 19, 314 10, 57 47, 138 14, 39 31, 155 18, 42 14, 4 22
Fabric 18
76 20, 280 11, 290 24, 1 16, 192 41, 52 17, 201 37, 288 21, 317 36, 320 0, 322 21, 47 21, 25 32, 290 22, 5 20, 207 4, 310 23, 17 15, 211 33, 212 15, 16 34, 350 13, 334 8, 3 36, 28 5, 84 12, 199 21, 200 47, 11 23, 93 47

Appendix 3: Aerial Photographs Used in Thesis

Figure Number	Photograph Identification
Figure 2.6	AS146 #46
Figure 3.12	AS4439 #172
Figure 3.14	AS865 #89, 90, 91
Figure 3.15	AS867 #79, 80, 81
Figure 3.17	AS865 #91, 92
Figure 3.19	AS 867 #24, 25, 26, 27
Figure 3.20	AS 867 #24, 25
Figure 4.9	AS4439 #232
Figure 4.11	AS4439 #235
Figure 4.15	AS4439 #233, 234
Figure 4.20	AS4439 #234, 235
Figure 5.3	AS4440 #95, 97, 99; AS4439 #237
Figure 5.5	AS4440 #186
Figure 5.8	AS4440 #186